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HUMAN ENGINEERING MAN-MACHINE STUDY

OF A WEAPON SYSTEM

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# HUMAN ENGINEERING MAN-MACHINE STUDY OF A WEAPON SYSTEM

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# I. ANALYSIS

The Human Engineering study has been aimed at making the weapon system more effective.

## A. INTRODUCTION

The general ground rules used in the study are as follows:

1. All the information which the crew needs and can use must be available with proper accuracy and range.

2. Information which is unnecessary or redundant should be eliminated.

3. Emergency operation must be possible in case of varying degrees of malfunction.

4. The cockpit information must be available in a reasonable form.

5. Displays and controls must be designed in accordance with best human engineering practice to permit maximum pilot contribution to mission success.

7. Equipment should be utilized to its maximum capability.

The human engineering development undertaken has involved both theoretical and experimental aspects. Insofar as possible, analysis and previous experimental work has been used to make the final recommendations. In several instances it has been necessary to determine answers to questions by experimental means.

The specific outcomes expected from the study program were stated in early 1957:

1. Develop a hardware recommendation for the front conckpit.

2. Study the advantages of other advanced cockpit systems.

   a. Navy O.N.R. contact analog
   b. WADC Integrated Instrument System
   c. Hughes Integrated System

3. Study the Phase I cockpit for difficulties or weaknesses.

4. Outline the mission and determine the pilot workload in terms of new knowledge of and a better definition of the ground environment and mission.

5. Develop an evolutionary Phase II cockpit system based upon refinements of the Phase I system.

Research was concerned with the development of

I. A. 6. Develop an "advanced" concept or revolutionary cockpit which would allow for ideal operation of ~~the~~ a weapon system. which utilizes manned interceptors,

7. Evaluate the study and make recommendations ~~concerning~~ future study needs.

Discussed are,

The results of the study are reported in two parts. This part describes the analysis of the problem, evaluations of suggested displays and a summary of the quantitative work accomplished. Part II will summarize the findings and make recommendations for the aircraft.

The study began with an investigation of the current air defense system employing broadcast control of F89 and F102 interceptors. The operational aspects of the air defense command on the squadron level were determined by interviews with personnel of the 432nd fighter squadron and from observing crews working out intercept problems on the Link F89 Simulator (Reference 1). Armed forces operations manuals were studied for general requirements of aircraft used in intercept missions. Preliminary studies were devoted to the specific weapon system problem and establishing a philosophy or approach to the problem.

Honeywell Phase I activity furnished the background for the beginning of the Phase II work. An advanced study program of future manned interceptor requirements provided information concerning the accuracy and dynamic requirements of a future system (Reference 2). Appendix C of this report is an extensive table of pilot workload in various general flight modes. This report contains system requirements as to information, accuracy, pilot action and ~~a discussion of~~ each flight mode of the future interceptor.

are discussed,

is studied.

B. COMBAT OPERATIONAL ANALYSIS (COA)

1. Introduction

The COA is a statement of the "events" which take place during the intercept mission, described in a time sequence (see Appendix 1). Our main concern was the point in the total weapon system loop at which the pilot must interact with the machine. The COA is therefore delineated from the pilot's point of view. "Events" refer to the individual control actions the pilot takes (stick movements, throttle movements, switch throwing, etc.) and the stimuli he receives from his instruments and from the external environment to his sensory receptors (instrument readings, listening to verbal information, etc.).

2. Sources of Information

a. Mission requirements were used as follows;

1) The main role of the aircraft shall be high altitude, all weather, night and day interception and destruction of enemy bomber aircraft.

I. B. 2. a. 2) The secondary role of the aircraft shall be low altitude all-weather night and day interception and destruction of airborne enemy bomber aircraft. However, the aircraft shall be designed to fulfill its primary role and limitations will be accepted in the fulfillment of its secondary role.

3) The crew shall consist of a pilot and an airborne interception radar operator.

4) The combat performance at combat weight shall be high speed and high altitude.

5) With the aircraft at normal gross weight and positioned at the ends of the runway, the elapsed time from the initiation of engine starting until the aircraft becomes airborne shall not be more than one minute.

6) The elapsed time required to reach a level flight high combat speed and a high combat altitude from the time the aircraft becomes airborne during take-off at normal gross weight under sea level conditions shall not be more than five minutes. The optimum climb and acceleration schedule shall be used.

7) Combat Radius of Action

The combat radius of action at normal gross weight shall not be less than that of a long range intercept. It shall be based on the following mission:

a) Scramble.
b) Combat climb and acceleration to high speed and attitude.
c) Cruise out at combat speed at high altitude to a distance of "x" nautical miles from base.
d) Combat under combat performance conditions and retaining armament for 5 minutes.
e) Return to base at economical cruising speed.
f) Loiter over base above 30,000 feet for 15 minutes.
g) Descent to sea level. (Distance covered during descent is not to be credited to the radius of action.)
h) Land with 5 minutes sea level loiter reserve remaining in fuel tanks.

I. B. 2. a. 8) The combat ceiling at combat weight shall not be less than "x" feet.

9) The aircraft shall be capable of taking off safely in still air at maximum gross weight from 6,000 feet runways at sea level and at a standard summer temperature of 38° C.

10) The aircraft shall be capable of landing safely in still air under NACA standard atmospheric conditions at maximum landing gross weight on 6,000 feet runways, at sea level.

11) Turn around time shall not exceed 5 minutes.

12) The aircraft shall be capable of meeting the scramble requirement of paragraph 5 with a delay of not more than 1 minute when dispersed in the open.

b. Information was provided on the operational aircraft's subsystems functioning. For the COA, a typical high speed mission was chosen as the problem which would provide the maximum load on the pilot. Following is the outline of the mission as calculated:

High Mach number, high altitude, aircraft starting weight of "X" pounds (includes: maximum internal fuel - "A" lb., "B" missiles = "C" lb.)

| CONDITION | TIME MINS. | FUEL LB. | DISTANCE N.M. | A/C WGT. LB. |
|---|---|---|---|---|
| Allowance to start engines | T | F | | X |
| Take-off to 50 feet (A/B lit) | $T_1$ | $F_1$ | | $X_1$ |
| Accel. to X MN (A/B Lit) | $T_2$ | $F_2$ | $D_2$ | $X_2$ |
| Climb to Y feet (A/B Lit) | $T_3$ | $F_3$ | $D_3$ | $X_3$ |
| Accel. to X MN (A/B Lit) | $T_4$ | $F_4$ | $D_4$ | $X_4$ |
| Climb to Y feet (A/B Lit) | $T_5$ | $F_5$ | $D_5$ | $X_5$ |
| Climb to Y feet (A/B Lit) | $T_6$ | $F_6$ | $D_6$ | $X_6$ |
| Cruise back at Y feet, X MN | $T_7$ | $F_7$ | $D_7$ | $X_7$ |
| Stack at Y feet (Max. End.) | $T_8$ | $F_8$ | $D_8$ | $X_8$ |

| | | | | |
|---|---|---|---|---|
| Descent to Sea Level | $T_9$ | $F_9$ | $D_9$ | $X_9$ |
| Land with 5 min. fuel remaining | $T_{10}$ | $F_{10}$ | $D_{10}$ | $X_{10}$ |
| TOTAL | $T_T$ | $F_T$ | $D_T$ | $X_T$ |

The cruise times and distances were modified for the COA in order to include an indentification pass..

I. B. 2. c. Interviews were held with current F89 jet interceptor pilots from 432nd Fighter Squadron, USAF, stationed at Wold Chamberlain Field in Minneapolis and with the 343rd Fighter Group at Duluth, Minnesota. The latter is one of the few groups in the country equipped with the Convair F102A interceptor, a delta-wing single place interceptor of somewhat less tactical capability than the aircraft understudy, yet the most modern operational supersonic interceptor available for study.

Mission procedures, cruise control problems and special handling techniques were defined and utilized, where applicable, in the COA.

d. Data on optimum and maximum climb, cruise and level flight altitudes and speeds were computed and made available by the Minneapolis-Honeywell Aeronautical Division Analysis Group. These were utilized in calculating the energy consumption and the duration of the discreet events (accelerate to X MN, climb to Y feet, accelerate to $X_1$ MN, etc.) in the COA.

e. Dunlap and Associates, under separate subcontract agreement, studied the mission and contributed an (Operational Analysis of a High-Speed, Short-Range Combat Mission . . . ," part of which was used as an outline for the COA

f. "Design Study and Recommendations for Cockpit Instrumentation for the Airborne Weapons Systems Phase I" and other information on the electronics to be used in the aircraft was studied.

I. B. 3. Procedure

a. Initially, the mission was divided into five operational phases:

1) Preflight and takeoff

2) Acquisition and identification

3) Attack and assessment

4) Return to base

5) Turn around

b. Then the information sources were used to derive the following:

1) The individual pilot actions

2) The controls and instruments which were being used during each of the pilot actions (This assumed the use of the proposed Phase I operational cockpit layout.)

3) The "present" and "desired" instrument readings (showing the discrepancy between the actual condition of the aircraft and the necessary change to the preferred mode)

4) The information needed by the pilot to meet the immediate mission requirement

5) The elapsed time in the mission, which was used to phase in events in the proper sequence

6) The mission time which was consumed by major events within each operational phase

7) The time required for the pilot to operate each of the individual events within the major events

8) The sensory channel through which the pilot received the information (i.e., visual, auditory, tactile, kinaesthetic)

9) The "motor" channel with which the pilot puts information into the system (i.e., hands, feet, speech)

10) The remaining fuel, distance flown and aircraft weight

I. B. 4. Results

The COA is found in Appendix 1 of this report. The COA represents the initial organizational step in the process of defining the optimum relationship of the pilot to the aircraft, "optimum" here meaning maximally successful completion of the mission through improved probability of kill. In the COA development process, operational unknowns of the A/C were defined, so that for the later, more detailed analysis, a still more extensive information search was possible.

The COA provided the skeletal outline of the mission which was used in the next analysis.

C. SECOND BY SECOND OPERATIONAL ANALYSIS (SSOA)

1. Introduction

The use of all the controls and instruments in the Phase I operational cockpit during the high speed intercept mission (as defined in the COA) was plotted in a second by second time sequence (Appendix 2). The ordinate of the two axis plot is this front cockpit listing. The abscissa represents elapsed time in the mission.

The pilot receives information from his instruments and from the external environment. These stimuli are received by various sensory channels (visual, auditory, tactile, kinaesthetic) and transmitted to his brain. The pilot makes control movements to put information into the weapon system. For this analysis his control(or "motor") channels include: hands, feet and voice.

The information the pilot receives from his instruments and from the external environment is referred to as "perceptual inputs to the pilot." The information which he puts into the total weapon system, including control movements within the aircraft and verbal intelligence spoken to the ground controller and the OBS/AI, is referred to as "motor outputs from the pilot."

In order to set down the events of the mission, coded symbols were developed. Perceptual inputs to the pilot include symbols for: observe in the cockpit, observe out, listen, sense by touch. Motor output symbols include: left hand, right hand, left foot, right foot, and speech. To describe the action that took place in each event, directional symbols were used, including: 1) up, increase, on, open, advance, in, forward; 2) down, decrease, off, close, retard, out, back; 3) left; 4) right; and 5) center, neutral, normal.

I. C. 2. Assumptions

a. The weapon system is functioning satisfactorily throughout the mission.

b. The Phase I operational cockpit layout was used, and was correctly arranged as described in Reference 4.

c. The pilot makes only "necessary" control movements and instrument readings. (This assumption has implications which will be discussed further in Section VI, Theoretical Use Frequency Analysis and Link Studies.) At the initiation of a transition in any axis we recorded discrete readings of instruments which would reasonably be used for that transition, but no attempt was made to theoretically derive reading and scan pattern techniques during the steady-state modes.

d. The pilot is well trained and always makes the correct decisions.

e. The mission profile occurs as described in the COA.

f. The aircraft is in standby, fully checked and prepared for immediate flight.

g. No ECM are encountered.

3. Sources of Information

The primary source of information for the SSOA was the COA, which was revised and expanded by new and corrected information. Other sources include all these detailed in the COA.

4. Procedure

Initially, all the instruments and controls in the Phase I operational aircraft were organized into eight basic flight parameter groups. The form of grouping was derived by seeking the most basic definitions of the frequently used terms: "Mission" and "weapon System." The existence of a "mission" to be accomplished was acknowledged as the prime mover in the development of the "weapon system" The definitions of the intercept mission which was provided is: "... high altitude, all-weather, night and day interception and destruction of enemy bomber aircraft." For the purpose of organizing the instruments and controls into groups which were mutually exclusive and which, in sum, were inclusive of everything which might possible be needed in the cockpit, the following definitions were derived:

I. C. 4.

Mission - the transfer and employment of destructive power from an origin to a particular point in space-time

Weapon System - energy which can be expended in a controlled manner.

Then, combining the two to give a statement of the weapon system being used to carry out the mission, we had:

"Energy which is expended in a controlled manner to effect the transfer and employment of destructive power from an origin to a particular point in space-time."

Analysis of this statement provided the basic groups under which the instruments and controls were organized, as follows:

1. Position of Aircraft in Space
2. Orientation of Aircraft in Space
3. Rate of Change of Position of Aircraft in Space
4. Energy (engines)
5. Biomedical Factors
6. Communications
7. Armament
8. Aircraft Sub-systems (miscellaneous)

The groups were numbered according to the expected frequency of use of each group. This form of grouping provided a logical location for the instruments and controls which facilitated the mechanics of the analysis. The individual instruments and controls in the front cockpit were arranged as follows:

I. Position of Aircraft in Space

1. Radar Attack Scope
2. | A/C Center
3. | Panel Intensity
4. | Scope Intensity
5. | Power access panel
6. |   RDY
7. |   MAL
8. IDD
9. | Input Select Switch
10. External Environment
11. Altimeter (turn to set)

I. C. 4.

I. 12. Command Altitude Counter
13. Target Altitude Counter
14. Magnetic Compass
15. AFCS Panel
16. | Flight Path
17. | On-off
18. | Navigation
19. Control Stick
20. | El. & Ail. Trim Sw.
21 | Trigger
22. | Damper Disconnect
23. | Nose Wheel Steer
24. Radar Overheat

II. Orientation of Aircraft in Space

1. FDAI
2. | Mode Select
3. | Horiz. Center
4. | Needle Adjust
5. Turn & Slip Ind.
6. Damper Control Pnl
7. | Power
8. | Engage
9. | Emergency
10. Rudder Trim
11. Control Surf. Pos. Ind.
12. | Rudder
13. | Aileron
14. | Elevator
15. Damping Out
16. Emerg. Damp.
17. R-P Axis Out
18. Damper Circuit Breaker Panel
19. | Normal A, B, C, DC
20. | Emergency A, B, C, DC
21. Rudder-brake pedals
22. Rud. Pedal Adjust. Cont.

III. Rate of Change of Position of Aircraft Through Space

1. IAS
2. Mach
3. Rate of Climb
4. Accelerometer
5. | Push to Set
6. Clock
7. | Set Knob
8. Throttle
9. | Speed Brake Sw.
10. Brake Chute Control Lever
11. Parking Brake

I. C. 4.

IV. Energy (engines)

1. EPI
2. Fuel Quantity
3. External Tank Quant.
4. External Tank Jettison
5. Fire
6. L.H.
7. HYD
8. RH
9. Second Shot
10. L.P. Fuel Cocks
11. Cross Feed
12. LH Only
13. Normal
14. RH Only
15. Eng. Fuel
16. Emerg.
17. Normal
18. Eng. Start L + R
19. Engine Relight L + R
20. Low Rotor O'Speed L + R
21. Oil Press L + R
22. Fuel Low L + R
23. Eng. Fuel Press
24. Fuel. Trans. Off
25. Ext. Tank Empty
26. Eng. Emerg. Fuel
27. Tank Jett. Fail.
28. RH LH Eng. Bleed Fail

V. Bio-Medical Factors

1. Air Cond. Fail
2. Cabin Press.
3. Cabin Press Altit.
4. Liquid Oxygen Quant. %
5. Air Cond. Panel
6. Temp. Coll-warm
7. Air Supply Norm., Off, Emerg.
8. Cabin Press. Damp.
9. Canopy
10. Close-off-open
11. Manual Canopy Lock
12. Emerg. Canopy Opening Lever
13. Seat Raising Handle
14. Oxy. Test Full Press.
15. Emerg. Oxy. Manual Control
16. Manual Narness Release
17. Composite Leads Disconnect
18. Anti-G Valve
19. Ejection Lever
20. High Alt. Lgt. On-off

I. C. 4.

V. 21. Main Panel Off-bright
22. Consoles Panels Off-bright
23. Console Flood - Off-bright
24. Ext. Lights Land-off-taxi
25. Nav. Lights Flash-off-stdy
26. Defog On-off

VI. Communications

1. UHF Control Panel
2. On-off
3. Volume
4. Channel Select
5. Tone
6. Input Select Off-main-both-adf
7. Radio Compass Control Panel
8. CW Voice
9. Volume
10. Tuning
11. Loop L-R
12. Bandswitch
13. Function Selects Off-adf-ant-loop-cont.
14. Inter-com Control Panel
15. Volume
16. Inter
17. Comp.
18. Comm.
19. Tacan
20. Tel.
21. Aux. Listen-normal
22. Channel Selector
23. IFF Control Panel
24. SIF Mode 1 10 position
25. SIF Mode 3 10 Position
26. IFF Master Off-stdby-low-norm-emerg.
27. Mode 2-out
28. Mode 3-out
29. I/P-out-mic.
30. Antenna Duplexer Control Panel
31. UHF Ant: Data Link Up, low-D.L.Low Up
32. UFF-IFF Emerg. Press to Test
33. Press to Talk Button
34. UHF Channel Indicators

VII. Armament

1. Armament Control Panel
2. Armt. Available SWL-SWR-FWD-REAR-None
3. Arm
4. Jettison
5. Launcher Retract
6. Armt. Select Sw-fwd-rear-all
7. Attack Select
8. Missile Hung
9. Stores Jettison

I. C. 4.

VIII. Aircraft Subsystems (Misc.)

1. Landing Gear Position Indicator
2. Lndg Gear Control Up-on-emerg. Exten.
3. Anti-skid Emerg. Off-norm.
4. Nav. Bail Out Button
5. Master Warn. Lts. Red-amber-nav. out Green
6. Master Warning Panel
7. Fly. Cond. Hyd (2)
8. Alternators Fail L + R
9. D.C. Fail L + R
10. Util. Hydraul.
11. Emerg. Brake Hydraul.
12. Ice
13. Press to Test
14. Press to Reset
15. Day-night
16. D.C. Reset
17. Master Electrical On-off
18. Alternators Start-trip
19. Battery Master
20. Lnd. Gr Wrn. Light
21. Battery Use

Later in the analysis the groups were considered as functional, unit-information sources. The validity of using the groups as whole integrated units in an advanced cockpit was considered in terms of contribution to mission success. The results will be discussed in the next section.

After the grouping procedure, each perceptual and motor event was recorded, with the appropriate symbol, as detailed in the introduction, and in the appropriate place to designate the instrument and/or control being used and the moment in time that it was used.

The three analyses which follow were derived directly from the SSOA. Appendix 2 is the final form of the SSOA.

D. THEORETICAL USE FREQUENCY ANALYSIS AND LINK STUDIES

1. Instrument Relationships

The "use frequency" of an instrument, as the name implies, is the number of times the instrument is used. This theoretical analysis is a plot of the estimated total number of times each instrument was used throughout the mission based upon present experience and the mission requirements. It is an indication of the relative importance of each instrument. (Figure 1)

I. D. 1.

This theoretical use frequency analysis was made directly from the SSOA. Assumption 3 in the SSOA indicates that the actual frequency of use is perhaps different because the instrument use during steady-state modes throughout the mission was not estimated. For example, whereas it was valid to assume that, at the end of a climb mode, where the pilot was trying to establish a certain altitude, he would make a certain minimum number of altimeter and rate of climb readings; it was not valid to assume any particular instrument scanning technique for the steady-state modes without considering the particular aircraft dynamics. For this reason the SSOA was a conservative statement of the instrument reading work per unit time that the pilot would accomplish during the mission.

For this analysis a "link" is defined as a shift from one instrument to another. The theoretical link study plots the links (greater than 1%) between each instrument with every other instrument in the front cockpit, expressed as a percentage of the total shifts for the mission (Figure 2).

In flight link studies have been made at Wright Air Development Center flying specific maneuvers, ground control approach and instrument low approach systems in aircraft such as the C-45 (multi-engine transport) and the T-33 (sub-sonic jet trainer). In these the frequency, duration and sequence of pilot eye fixations was taken from films made of the pilots' eye movements during flight. Table 1 compares these percent link values, and indicates difference (above 1%) between the aircraft understudy during the entire intercept mission and the T-33 during an ILAS mode and the average values of all the various modes of the in-flight studies.

Because examination of the individual instruments shows that the differences between the theoretical and the in-flight studies are explainable in terms of different aircraft, flight modes, instruments, and the fact that the steady-state scan mode was not estimated in our study, the in-flight studies tend to support the validity of the theoretical analysis.

The results of the theoretical analysis indicate generally that the cockpit is well laid out using the proposed instruments. The application of the link study information will be discussed further in Part 2, "Recommendations."

2. Group Relationships

Theoretical link relationships between the groups are shown in Figure 2. If grouping such as this is to be used to organize the cockpit, it is necessary to examine the functional validity of the grouping.

I. D. 2.

A calculation was made of the ratio of the use within the group to the use between the group and all other groups to help determine the relative validity of the grouping.

| Group | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| $\frac{\text{Internal Use}}{\text{External Use}}$ | .065 | .033 | .153 | .104 | .226 | .279 | .591 | .342 |

It was reasoned that a group which is primarily linked to other groups and with few internal links would not be considered a good grouping, and, conversely, those groups with many intra-group links and few inter-group links would be useful groups. It was further reasoned that many inter-group links for a given pair or set of groups would be a good basis for an integration of the separate components of the involved groups into one group.

The results, taken from Figure 4, are as follows:

1. Groups 1, 2 and 3 have a predominance of inter-group links among themselves, and they are relatively poor separate groups; therefore, it is indicated that these groups would be suitable for integration. Using the ratio, as above, of internal to external links, the value for groups 1, 2 and 3 considered as one group is 0.779.

2. The link values of group 4 are almost evenly spaced among all the other groups. Because of weak intra-group links it is a poor group by itself. However, it is related to groups 1, 2 and 3 (considered as a whole).

3. Groups 7, 8, 6 and 5, in that order, are relatively valid groups. The ratios for these groups suggests integration individually within each group.

4. There is no functional relationship between groups 5 and 6, 4 and 7, 7 and 8.

| | | Our Aircraft | WADC Desc. Turn | GCA | ILAS | Climb Const. Hdng. | Desc. Const. Hdng. | Climb Turn | Level Turn | T-33 ILAS | Average | Major difference between our aircraft and T-33 ILAS | Major difference between our aircraft and Aver. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| IAS+Mach | Alt | 1.7 | 7 | 4 | 0 | 9 | 8 | 7 | 8 | 2 | 5.6 | - | 3.9 |
| " | IDD | 7.3 | 17 | 29 | 11 | 16 | 18 | 15 | 13 | 12 | 16.4 | 4.7 | 9.1 |
| " | FDAI | 5.9 | 8 | 6 | 10 | 10 | 10 | 7 | 5 | 12 | 8.5 | 6.1 | 2.6 |
| " | R/C | 0 | 3 | 0 | 0 | 4 | 4 | 2 | 0 | 0 | 1.6 | - | 1.6 |
| " | EPI | 1.4 | 0 | 0 | 0 | 2 | 3 | 0 | 0 | 0 | .6 | 1.4 | - |
| Alt | IDD | 2 | 4 | 4 | 0 | 3 | 3 | 4 | 7 | 4 | 3.6 | 2 | 1.6 |
| " | FDAI | 2.8 | 3 | 0 | 0 | 0 | 2 | 4 | 7 | 2 | 2.3 | - | - |
| " | R/C | 1.1 | 0 | 0 | 0 | 2 | 3 | 3 | 4 | 0 | 1.5 | 1.1 | - |
| " | EPI | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | - | - |
| IDD | FDAI | 9.9 | 22 | 30 | 22 | 21 | 21 | 23 | 25 | 27 | 23.9 | 17 | 14 |
| " | R/C | 0 | 3 | 5 | 0 | 3 | 2 | 3 | 3 | 5 | 3 | 5 | 3 |
| " | EPI | 0 | 3 | 3 | 0 | 0 | 3 | 3 | 0 | 0 | .38 | - | - |
| FDAI | R/C | 1.1 | 8 | 5 | 2 | 11 | 9 | 9 | 8 | 5 | 7.1 | 3.9 | 6 |
| " | EPI | 0 | 5 | 0 | 0 | 4 | 5 | 4 | 0 | 0 | 2.3 | - | 2.3 |
| R/C | EPI | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | - | - |

TABLE I

EYE MOVEMENT LINK VALUES BETWEEN AIRCRAFT INSTRUMENTS

Theoretical Values for Our Aircraft Compared to
In-flight Studies on C-45, T-33 and the Average (Percent Links)

# I. E. PERCEPTUAL AND MOTOR INFORMATIONAL ANALYSIS

## 1. Introduction

### a. Theory

"Information Theory," a relatively new field of scientific investigation maintains that an exchange of intelligence (or information) can be quantitatively analyzed and that the nature of the exchange, the rate, and quality can be predicted and coding principles can be specified. A basic unit of information can be defined and validly applied to any intelligence source, regardless of the particular energy form of the information. The "bit" is the unit measure of information (condensation of "binary digit"). It is equal to the logarithm to the base 2 of the number of equiprobable alternatives which are available at a given time. If "n" is the number of equiprobable alternatives, the information "H" in bits is equal to the exponential to which 2 must be raised to equal "n", i.e.: $\log_2 4 = 2$, $\log_2 8 = 3$, etc. Thus, a two-position, labeled switch would provide one bit of information by its position as a perceptual input to an observer (i.e.: he sees the position of the switch). This is true in the case where the alternatives are equiprobable. However, if the observer had reason to believe that the switch is three times more likely to be in the first position than the second position, then, generally,

$$H \text{ bits} = -\sum p\, i \log_2 p\, i,$$

where "p" is the probability of occurrence of "i", one of the alternatives, and specifically where $p_1 = .75$ and $p_2 = .25$,

$$\begin{aligned} H \text{ bits} &= -(p_1 \log_2 p_1 + p_2 \log_2 p_2) \\ &= -(-.3113 - .5000) \\ &= .8113 \text{ (bits of information).} \end{aligned}$$

If, instead of looking at the switch to gain information, the operator elected to throw the switch to some position, he would have committed a "motor output" to the system of .8113 bits of information.

I. E. 1. b. Context

The context of this intelligence exchange is a "system." Intelligence is put into and taken from a system to accomplish some goal. We are concerned with the information exchange in the weapon system and with the rate at which information is exchanged.

c. Rate

A concept of "channel capacity" has been established in information theory, two formal definitions of which are:

1) If the stimulus-response matrix is known, then there exists a set of stimulus probabilities such that the information transmission is maximized.

2) If the input probabilities and the physical characteristics of a channel are known, then there exists a code such that the information transmission is maximized; the rate obtained by either method is called channel capacity.[9]

But neither approach is very useful when working with man; a poorly known and poorly controlled channel.

Licklider[9] performed several direct experiments to empirically determine maximum channel capacity. The first of these was a simple perceptual identification (select blackened squares, placed at random, in a matrix of white squares) followed by a simple motor response (mark the black squares). The highest rate was 15 bits per second. For reading random sequences of words at rapid speed, Licklider found that the transmission rate rose with increasing vocabulary to a plateau of about 25 bits per second. By combining the two tests, the total rate went up to 35 bits per second. No substantial improvement beyond this point was found. H. Quastler[9] estimated the rate of information transmission for oral reading of coherent English texts and the informational yield of high speed mental arithmetic and in both cases arrived at a rate of 24 bits per second.

A methodical investigation of the limits of information transmission (15) in typewriting (random texts) and playing piano by sight (random music) resulted in a range of values from 1 to 27 bits per second for alphabets of 4 to 65 possible choices. The plateau of highest transmission rate was established

I. E. 1. c.

when using a set of 37 equiprobable choices (keys, in the piano tests). The results of these tests are summarized in these three rules:

1) In the neighborhood of peak transmission, information transmission is limited by a highest effective speed, a highest effective range, or a highest transmission rate, whichever imposes the lowest limit.

2) If the stress in one direction (speed or range) is small, then the limitation in the other is somewhat relaxed, ("Simple challenge effect").

3) Attempts to go much beyond the highest effective speed, the highest effective range, or the highest transmission rate result in lowered performance: "confusion effect."

An attempt to summarize all the data on human channel capacity to arrive at one clear-cut figure which would apply to the Phase II information analysis proved impossible within the scope of this study, because of a wide variety of results which experimenters have obtained. However, in the research one pattern became reasonably clear, and using a simplifying assumption, the available evidence was utilized for our analysis.

In Crossman's study(11) an attempt is made to explain the wide variation from task to task in information capacity. He points at a fundamental difference between two task types. The first is the non-symbolic, where the response is in direct mathematical correspondence with the display, defined: "If a unique algebraic transformation can be applied to the error signal displayed to the operator and give the response to be made by him, with a definite point or region of zero-error previously selected by him, the task is non-symbolic." All other task types would be "symbolic." In the latter, the error must be translated instead of transformed. The symbolic task therefore involves coding (statistically, as defined by Shannon) and is much more flexible. In engineering terms, the human operator "may act either as a continuous (non-symbolic) or as a digitally operated (symbolic) servo-mechanism."(11)

# I. E. 2. Information Analysis (Appendix 3)

## a. Procedure

The Perceptual and Motor Information Analysis which was conducted for the Phase II program is a statement in tabular form of each discrete information exchange between the pilot and the remainder of the weapon system. A list of each instrument (Column C) and control (Column e) usage in time sequence is provided along with the accuracy (Column d) with which each is used at the given movement. Then the number of possible equiprobable choices (Column k) which are available to the information receiver is set down and, from this, the "bits" of information (Column j) is derived according to the formula:

$$H_{bits} = \log_2 n$$

where "n" is the number of possible equiprobable choices. From this the time durations (Columns f, g, h, i) of each exchange were determined by using appropriate rates of information transmission, as discussed below. Any special cases are discussed in the Notes (referenced in Column O) which are found at the end of the appendix.

Account is made of elapsed mission time (Column a), and the sum of the exchanges for each ten-second interval is provided in terms of total bits, total time occupied, and percent of the ten-second interval occupied (Columns l, m, and n respectively).

The analysis was derived directly from the "Second by Second Operational Analysis" and the coding used (Column b) is identical with the coding employed in the SSOA.

## b. Rate

By classifying the data from Crossman's study and the evaluations which were performed by other experimenters 15-20, 24, 25, according to symbolic and non-symbolic tasks, rough values for each category, of 5 bits per second and 20 bits per second, respectively, were chosen for the Information Analysis. The applications of these rates to the analysis was done on a logical basis, correct to the degree to which the tasks could be clearly defined as symbolic or non-symbolic.

## I. E. 2. c. Special Problems

The verbal communication between the pilot, the observer and the ground controller presented a special problem. According to Frick and Sumby[21], "A sub-language of the general English language was selected for study. Because the set of possible messages of the sub-language was less than the set of possible messages of the parent language, less information per word is transferred with the sub-language; it is more redundant. The linguistic structure of English is about 60 percent redundant relative to the information transferred with the same number of letters arranged in random order. When the situational restraints of the control tower language are also taken into account, its redundancy is raised to 96 percent."

A figure of 75 percent redundancy was used in the Information Analysis for all verbal communication because it was reasoned that the language employed during the intercept mission would be a sub-language of the general English language, but would have less situational restraint than the control tower sub-language. Note #3 in the analysis describes the technique for arriving at the information and time value for a given verbal message.

Where applicable, Figure 4[22] was used for motor actions in the Information Analysis, to establish physical movement (control) times. Reaction time based on the complexity of the discrimination needed was computed from the following equation:

$$R_T \text{ (milliseconds)} = 270 \log_e (n + 1),$$

where n = the number of discriminations required before reacting.[9]

Any additional special cases are discussed in the notes which follow the analysis. Figure 5 is a summary of the Pilot Work Load plotted graphically, taken from the values obtained in the Information Analysis. This is a very conservative estimate in that it is not corrected for the steady-state instrument monitoring activity of the pilot. The latter was experimentally determined in the Minimum Control Time Studies which will be discussed in the next section.

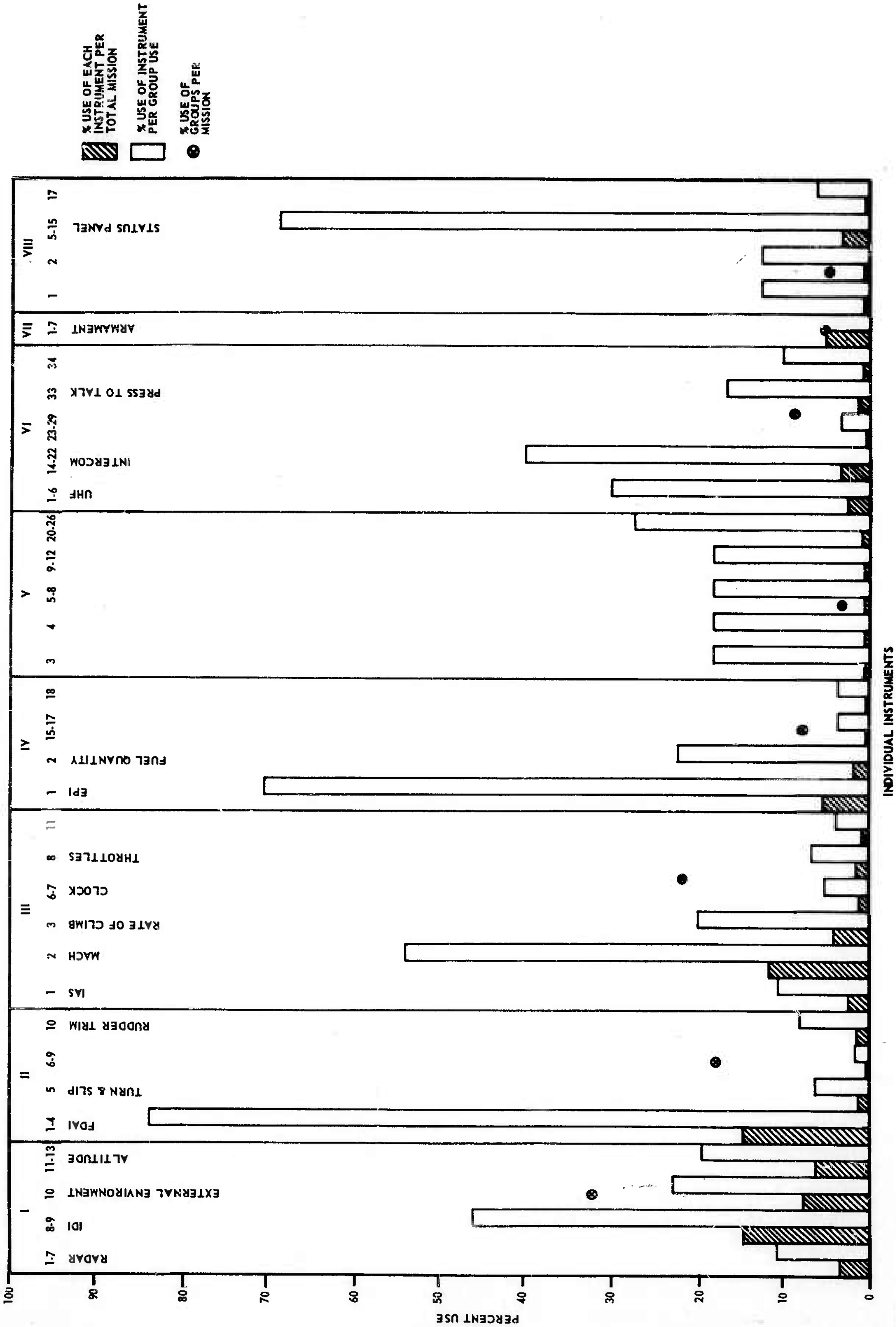



**Figure 1. Use Frequency Analysis**

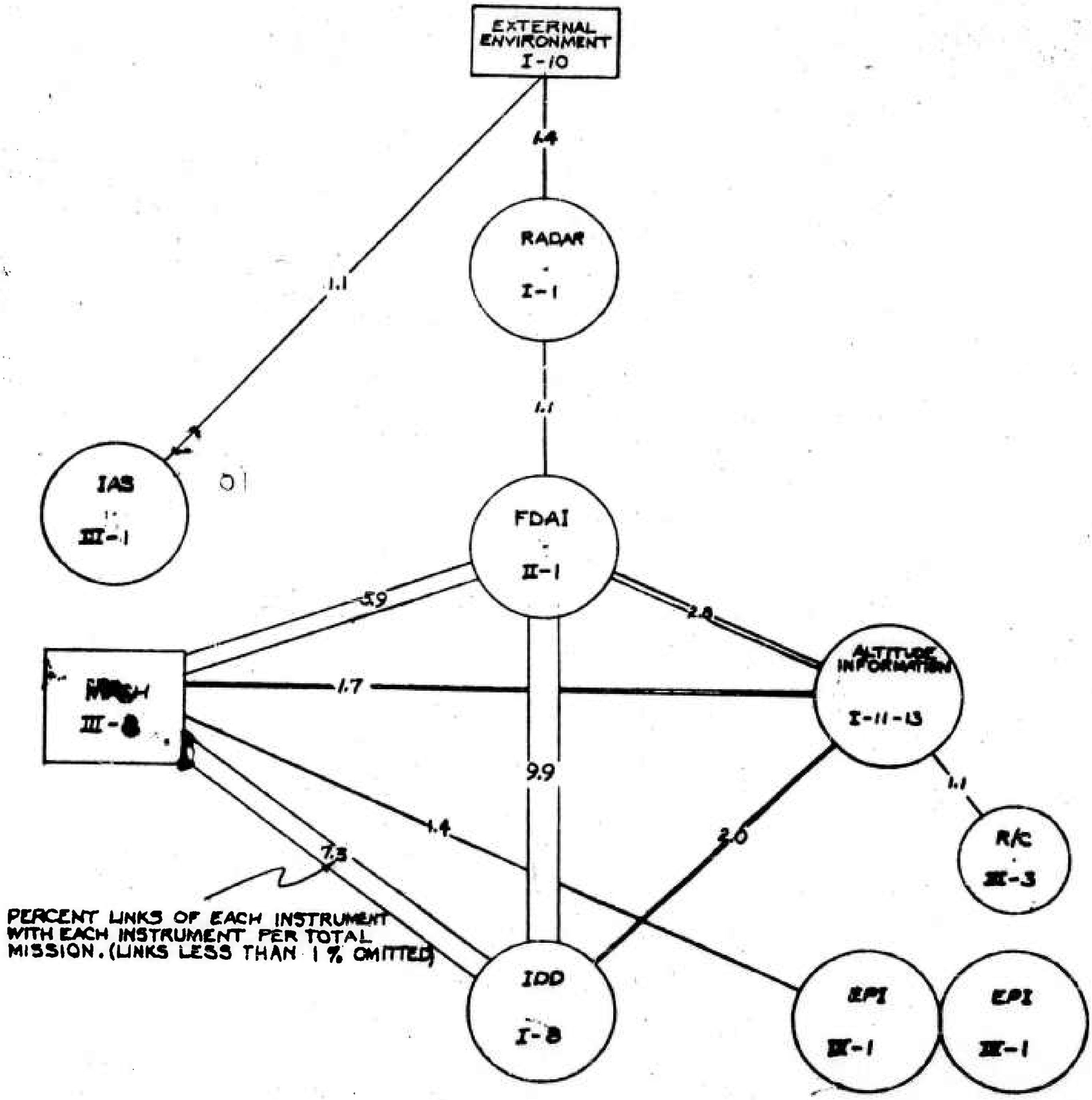
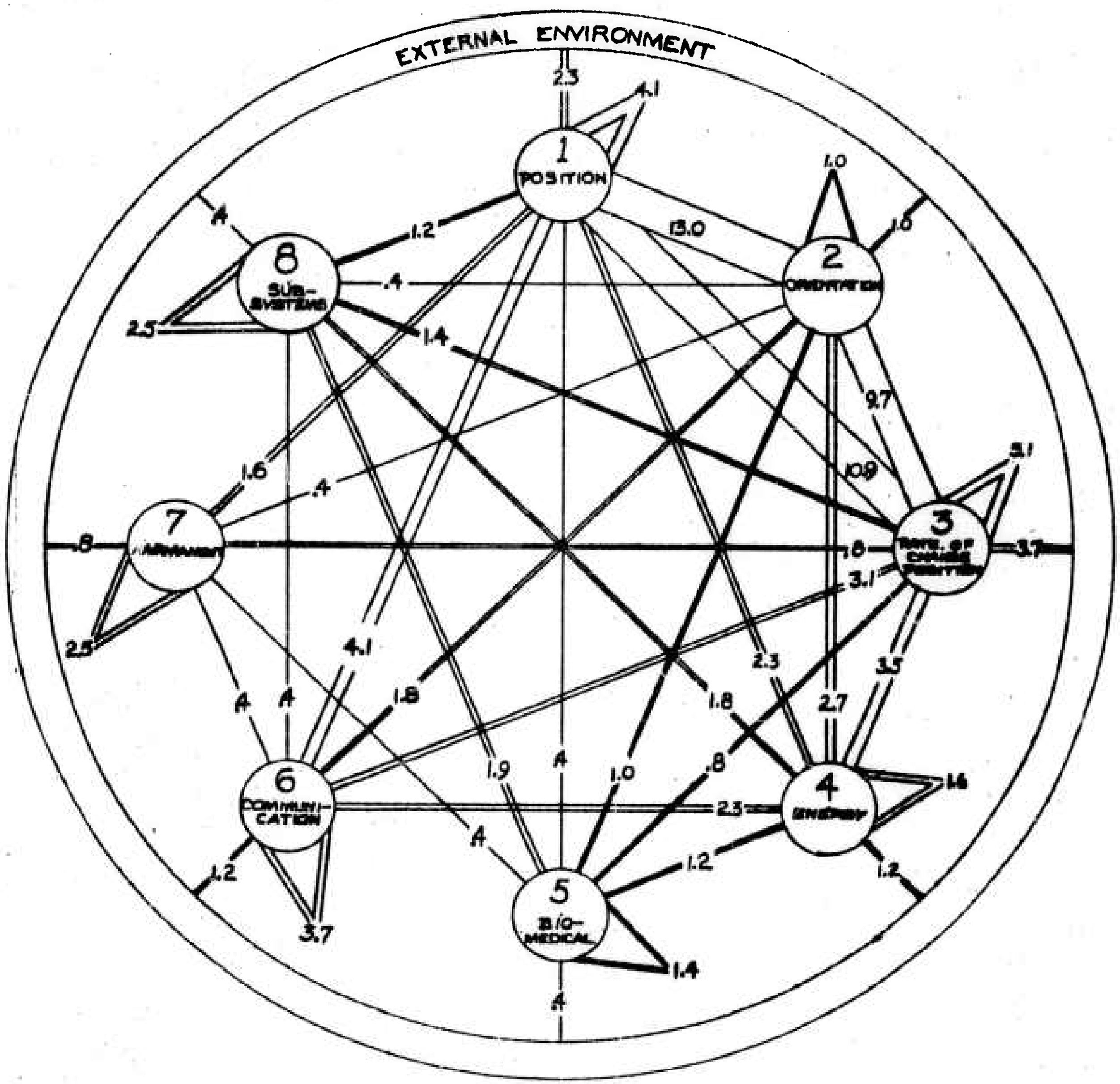



Figure 2. Theoretical Instrument Link Study




PERCENT OF USE FREQUENCY-GROUPS/TOTAL MISSION

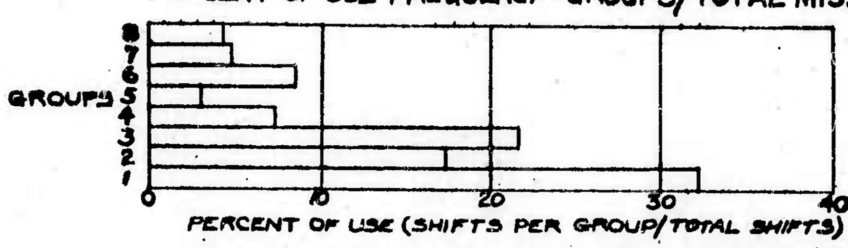



Figure 3. Theoretical Eye Movement Link Study

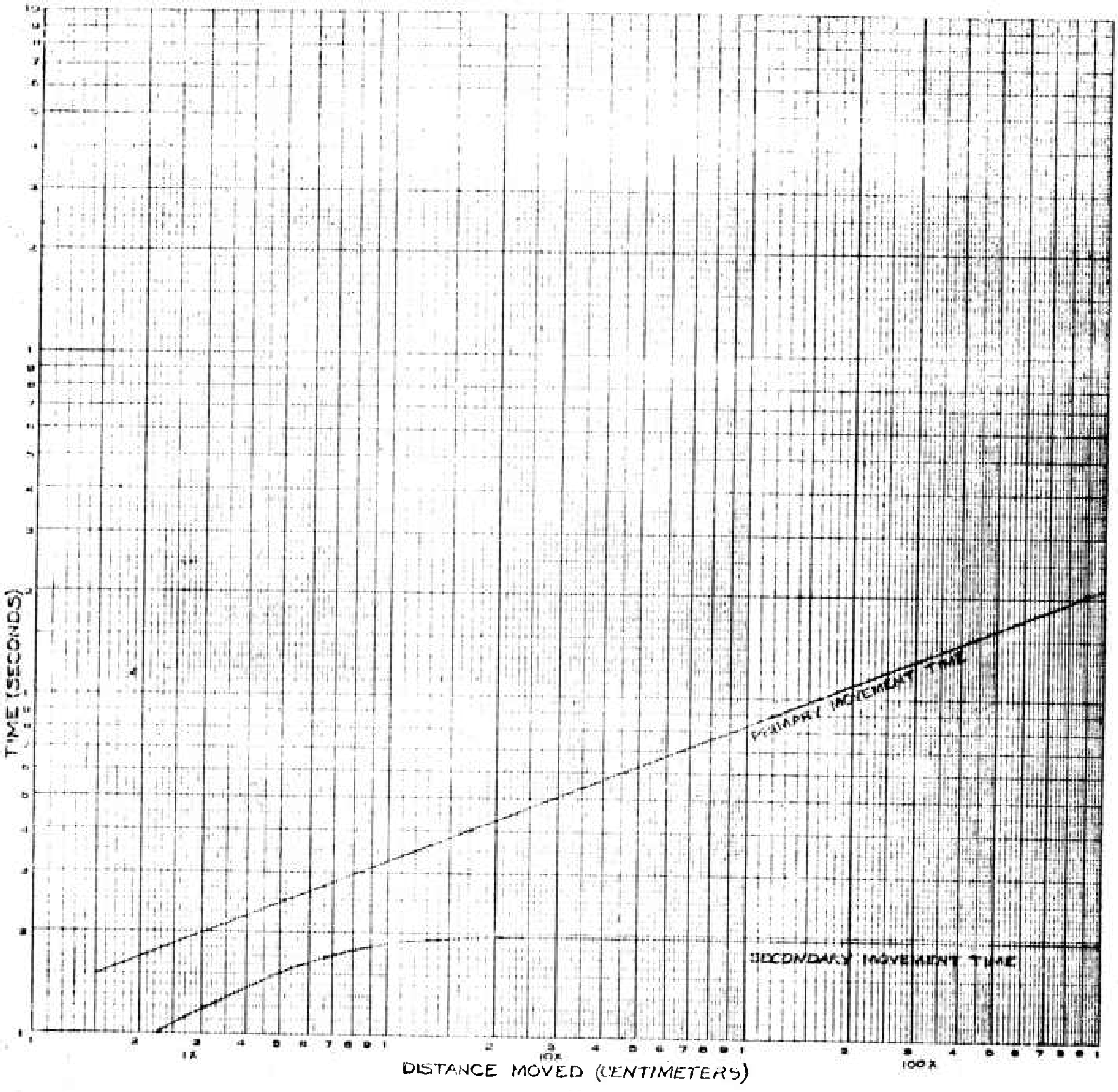



Figure 4, Time as a Function of Distance Moved

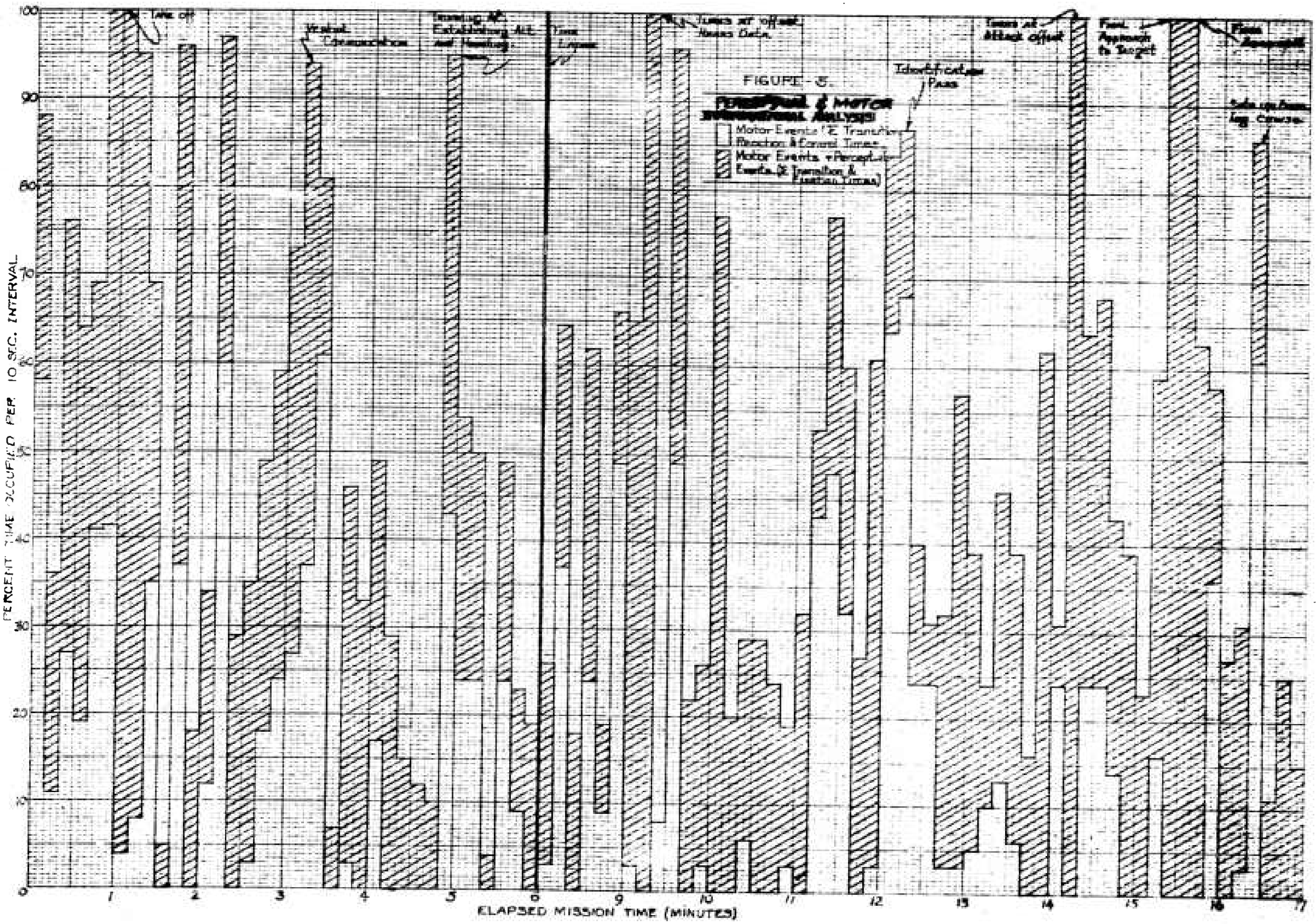



Figure 5 **Perceptual** and Motor **Informational** Analysis

Table 1. Eye Movement Link Values between Aircraft Instruments. Theoretical Values Compared to In-flight Studies on C-45, T-33 and the Average (Percent Links)

| | | | WADC Desc. Turn | GCA | ILAS | Climb Const. Hdng. | Desc. Const. Hdng. | Climb Turn | Level Turn | T-33 ILAS | Average | Major Difference between T-33 ILAS | and Average |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| IAS + Mach | Alt | 1.7 | 7 | 4 | 0 | 9 | 8 | 7 | 8 | 2 | 5.6 | - | 3.9 |
| " | IDD | 7.3 | 17 | 29 | 11 | 16 | 18 | 15 | 13 | 12 | 16.4 | 4.7 | 9.1 |
| " | FDAI | 5.9 | 8 | 6 | 10 | 10 | 10 | 7 | 5 | 12 | 8.5 | 6.1 | 2.6 |
| " | R/C | 0 | 3 | 0 | 0 | 4 | 4 | 2 | 0 | 0 | 1.6 | - | 1.6 |
| " | EPI | 1.4 | 0 | 0 | 0 | 2 | 3 | 0 | 0 | 0 | 0.6 | 1.4 | - |
| Alt | IDD | 2 | 4 | 4 | 0 | 3 | 3 | 4 | 7 | 4 | 3.6 | 2 | 1.6 |
| " | FDAI | 2.8 | 3 | 0 | 0 | 0 | 2 | 4 | 7 | 2 | 2.3 | - | - |
| " | R/C | 1.1 | 0 | 0 | 0 | 2 | 3 | 3 | 4 | 0 | 1.5 | 1.1 | - |
| " | EPI | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | - | - |
| IDD | FDAI | 9.9 | 22 | 30 | 22 | 21 | 21 | 23 | 25 | 27 | 23.9 | 17 | 14 |
| " | R/C | 0 | 3 | 5 | 0 | 3 | 2 | 3 | 3 | 5 | 3 | 5 | 3 |
| " | EPI | 0 | 3 | 3 | 0 | 0 | 3 | 3 | 0 | 0 | .38 | - | - |
| FDAI | R/C | 1.1 | 8 | 5 | 2 | 11 | 9 | 9 | 8 | 5 | 7.1 | 3.9 | 6 |
| " | EPI | 0 | 5 | 0 | 0 | 4 | 5 | 4 | 0 | 0 | 2.3 | - | 2.3 |
| R/C | EPI | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | - | |

## F. EXPERIMENTAL DETERMINATION OF PILOT WORK LOAD IN CONTROLLING THE AIRCRAFT IN ITS VERTICAL AND LATERAL AXES

The previous studies determined pilot requirements in the areas not associated with the continuous control problem. An estimate is also necessary of the difficulty the pilot will experience in flying the airframe apart from its switches, communication system, radar and other equipment. The necessary accuracy of the determination of the continuous control problem is a relative matter. The aircraft's stability augmentation is designed to reduce the complexity of the manual control task to a reasonable level. Since no information exists concerning the actual work load of a pilot in any aircraft resembling the one under study, an analysis was necessary to establish a figure of merit.

### Introduction

The modern specification of a control system is characterized by an analysis of the dynamic characteristics of the system. This analysis is usually performed using a computer simulation of the system to study responses to step or sine-wave inputs. In the case of cockpit specification or design a more complicated situation occurs due mainly to the variable nature of the human operator. The Phase II cockpit study has concerned itself with designing a pilot's cockpit by an analytic procedure which has made use of experimental techniques which include the pilot's response characteristics and requirements. The experimental evaluation of the aircraft control characteristics and man relationship is the concern of this report. The assumptions and approximations which were used are outlined, and the degree of confidence expressed.

Early in the study it was decided that quantitative evaluation criteria must be used as a basis for recommendations for the cockpit displays. The analysis of pilot work load is an obvious necessity for any recommendations since some suggested improvements may be irrelevant or trivial. Improving an instrument by 10 percent at a high cost may not be warranted if it is only used twice during cruise conditions where ample pilot time is available.

It is a common "cliche" to state that the pilot is overloaded and that he needs improved controls and displays but the missing link has been a systematic method of determining specific pilot problems and the value of improvements. The concern of our study is to find a specific answer to the following questions:

1. Is the pilot overloaded and if so, how much?
2. What is the principle cause of the overloading?
3. What effect will the overload have on mission success? i.e., how much loss of kill probability is involved because vertical and steering errors will occur due to overloading?

4. If a new system or improved display is utilized, how much will it help the pilot's overall performance?

5. Which functions should be automatic and which manual?

As a part of the data necessary to specifically improve the aircraft, a dynamic response of the man-machine interaction was determined. If the actual aircraft were available for eye movement and work load study, the analysis could have been airborne. Since this was impossible the study had to be made using the analog computer and operational pilot's flying experimental problems. Experiments were designed to determine the extent of the control problem the pilot would have flying in the damper mode. By knowing the extent and nature of the pilot work load, it is possible to specify the maximum benefits which can be effected and the system improvement sought.

## Method

Consider a completely automatic aircraft lateral beam following system as found in Figure 6.

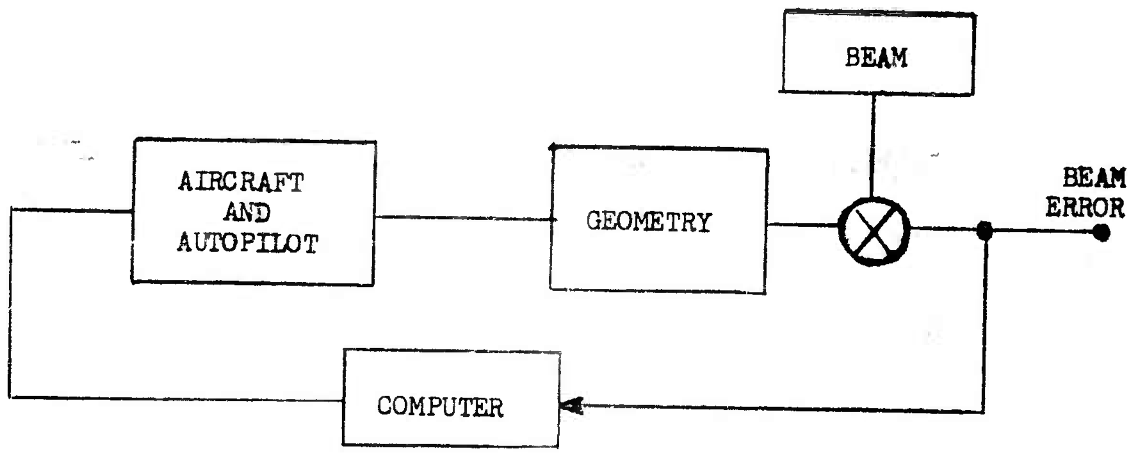



Figure 6. Lateral Beam Following System Block Diagram

Studying this system from the point of view of dynamic stability it can be seen that each element of the closed loop system must be considered if a proper picture is to be obtained. Assume the aircraft and autopilot combination to be a high-performance stable system which can be described in terms of a transfer function. The geometry can be approximated at a particular flight condition by integrating bank angle to obtain heading and integrating heading to obtain displacement. This displacement relative to the beam furnishes an error signal to the computer which develops a

proper corrective signal to introduce into the autopilot. This simple system can be designed so that with a continuous data flow, a satisfactory critically damped performance can be obtained. The computer is assumed to be analog in this case.

Suppose we now alter the system and introduce a digital computer with a sample and hold circuit, a data sampling system. The system operates on the actual beam error during sample but retains the last sampled value during hold. The computer sampling rate can be varied to determine the effect of data sampling on system performance. This technique has been used to determine the amount of digital computer time or facility required for satisfactory system operation.* As expected, with a high sampling rate no difference is noted between a continuous analog solution and a finite time digital computer solution time. If minimum computer requirements are sought, the high sampling rate would be undesirable. It can be shown, however, that a deterioration of performance will occur at a particular sampling rate and that complete instability will occur at a lower rate. Changing the gain of the system changes the sampling rate required. Figure 7 is taken from Reference 1 and summarizes the results of a study of this type of analysis.

The pilot in normal operation performs a similar function. He scans his instrument panel obtaining sufficient information to control his flight. The amount of time he spends on any information source is dependent on the nature of the problem he seeks to solve. The eye movement or link studies conducted by WADC are reflections of the problem of flying the planes (C-45 and T33) and the manner of reading traditional instruments used in the experiments.**

It is theoretically possible to repeat the digital computer sampling determination using the accepted experimentally determined human transfer function, the transfer function of the control system and special sampling servomechanism techniques. This has been tried in the Aero Research Department of Honeywell and found inadequate because of the tremendous computation involved and the inability to define a human transfer function. An experimental check of the simplest possible system we could analyze indicated that a skilled operator would not remain in a hypothesized simple transfer function behavior when given low sampling rates. It was therefore concluded that an experimental approach was necessary to determine the minimum amount of information input to the pilot which would allow satisfactory control. Figure 8 is a block diagram of the general technique used.

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* Memo: H. Gustafson and O. Pomeroy to R. J. Keeler, June 6, 1956, Subject: The effect of Data Rates on Beam Following Characteristics of a High-performance Aircraft.

**Fixations during Zero-reader Approaches in a Jet Aircraft (eighth of a series) ATI 149050, February 1952, Milton, J. L., Wolfe, F. J.

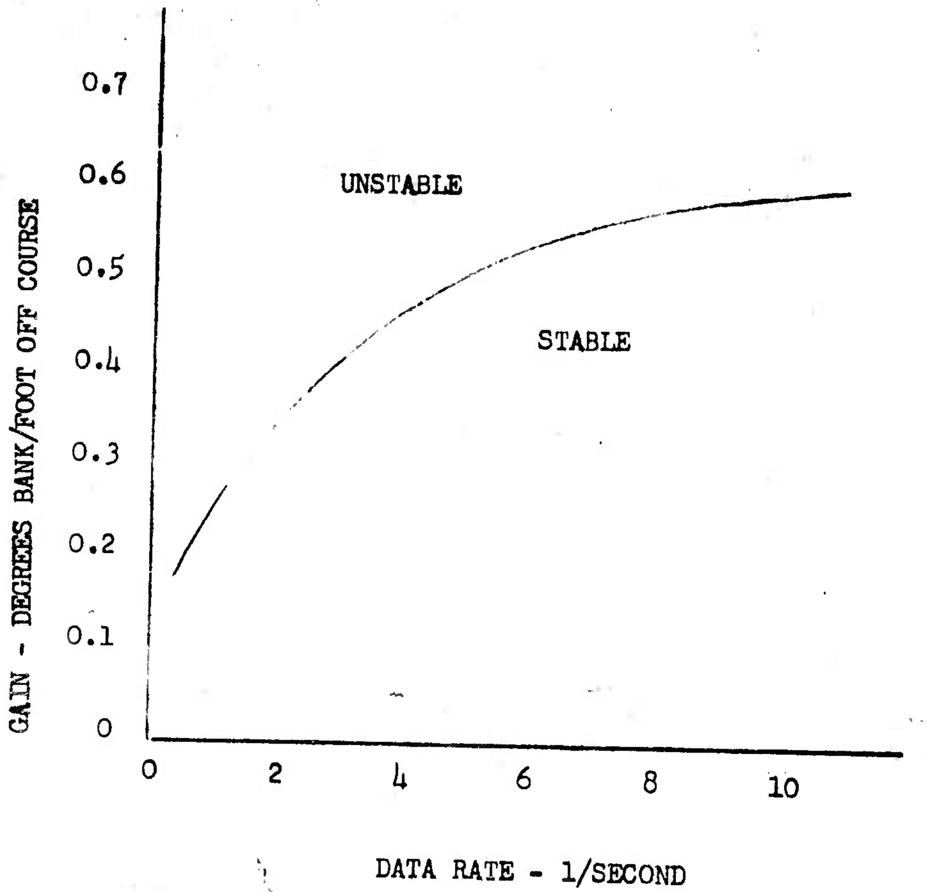


Figure 7. Gain for a Neutrally Stable Navigation System versus Rate at which Error Data is Supplied

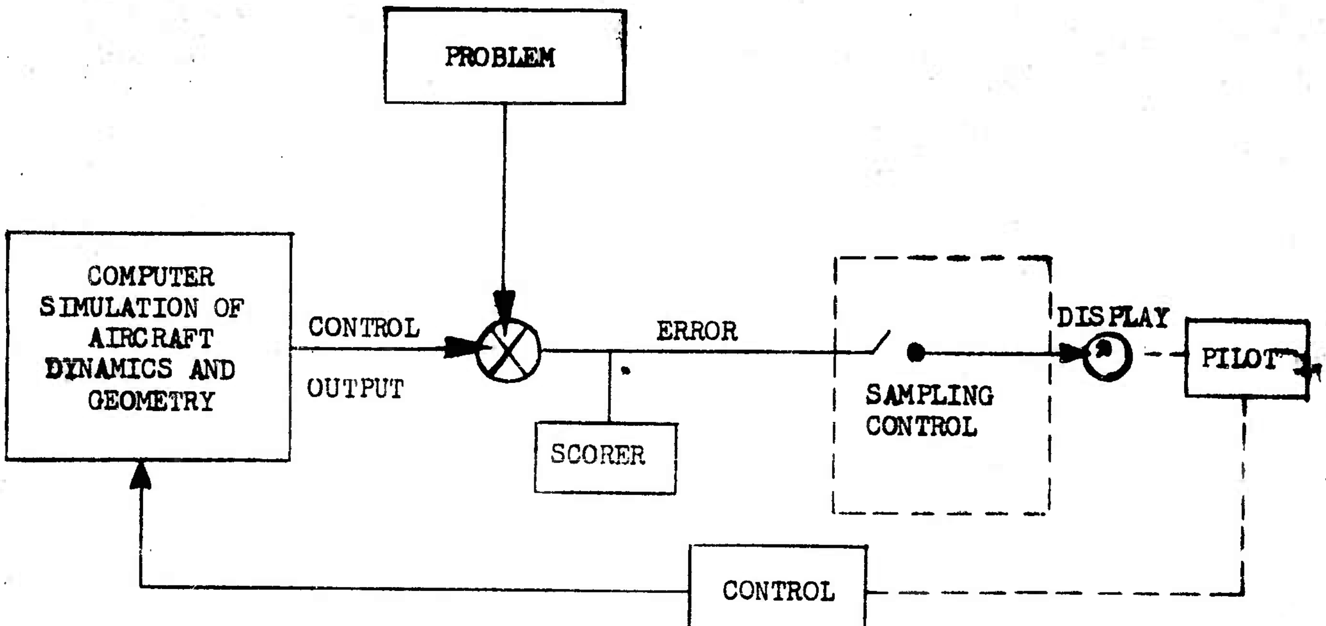


Figure 8. Minimum Information Transfer Diagram

The pilot is presented information at a controlled rate. He then acts as the computer of Figure 6 and controls the system. The simulation is varied to present different flight conditions. This technique is similar to changing system gains of the previous discussion. The flight conditions were chosen to represent the typical operating flight regions of the aircraft mission. The system performance was scored for evaluation purposes.

The experimental analysis of continuous pilot input into the aircraft was confined to the lateral and vertical axis control problems. In order to conduct a meaningful experiment the two axes were studied separately. It is assumed that the pilot would not be able to handle the two control axes more efficiently together than separately, as far as informational requirements and stick movements are concerned. If this is the case, one can determine each axis work load separately and simply add the two values together to obtain a reasonable minimum total. This would be analogous to finding data sampling rates for the pitch and lateral axis separately and adding these to determine the total requirements. It is thought that this is a reasonable assumption leading to a minimum work load since the actual configuration in flight would add complications such as coupling between the axes and more complex instrument interrelationships.

The values obtained in the experimental work have to be modified to reflect the type of instrument dials and number of information sources found in the cockpit. The process for this will be discussed later in this section.

The values which are experimentally found in the evaluations described in this report are incorporated with other data concerning the cockpit. By this means a quantitative look at the cockpit problem is obtained which is directly related to the control problem of the aircraft.

By assuming a minimum pilot control input an estimate is also made of pilot work load while using the autopilot.

## Interpretation of Experimental Data in Terms of the Aircraft Cockpit

The experimental value of minimum viewing percentage is expressed by a ratio of "on" or viewing to "off" or no display time. Each flight condition is characterized by a fixed requirement of minimum "on" to "off" time for best control. This data must be then interpreted in terms of the aircraft's instruments. If the displays used in the experiments corresponded to the actual instruments, the data would be directly applicable. Since the experimental displays were somewhat different from the actual, a correction factor must be introduced into the work load analysis.

The experimental value was found by having an "on" time of 0.25 second and a variable off time. The "on" time was chosen by considering the available data regarding visual perception and also by experimental feasibility. The experiment then established a particular off-time at which point pilot performance was found to deteriorate.

The "off" or no display time which we determined experimentally represents the amount of time a pilot can leave the axis of control information without losing some degree of control. Since the off-time could be decreased before a change in pilot performance was noted, it can be assumed that the system-man combination was such that effective pilot inputs were limited. Continuously observing vertical axis information provided more information than could be used. By lengthening the "off" time until pilot performance was degraded, the point of minimum percentage of viewing time for maximum control was established.

For maximum pilot contribution to the pitch axis the "off" time could not be increased since it was a function of the man-machine dynamics, not the display. The "on" time represents the amount of time necessary to gain information from the displays. If a single hypothetical instrument existed which could yield the proper information it might have a characteristic reading or interpretation time different from the 0.25-second exposure time used in the experiment. The minimum viewing percentage for maximum control would vary directly with this difference.

The problem is then to determine the interpretation time of the hypothetical instrument. In using his cockpit instruments the pilot continually scans his instruments. Information concerning the control of a parameter such as speed is intermittently received according to the requirements of that system and the press of other duties. Typical instrument scan patterns have been experimentally determined by Jones, Milton and Fitts.* Movies of eye movements were taken of pilots flying normal maneuvers in actual aircraft. It was found that each cockpit instrument had a typical viewing time and frequency of observation. The number of transitions or changes from instrument to instrument was established. The transition time or amount of time a typical transition required was also calculated. Each maneuver had a unique pilot instrument reading technique which is reflected in a changed scanning procedure.

The Phase I cockpit of the aircraft contains a display system very comparable to the conventional instrument system used in the WADC eye movement studies. It is therefore reasonable to assume that the relative use frequency of the instruments will be comparable. In a climbing turn the WADC eye movement studies showed the following data:

| Instrument | Number of Fixations/Min | Percentage of Time on Instrument |
|---|---|---|
| Air Speed | 17 | 16 |
| Directional Gyro | 26 | 23 |
| Gyro Horizon | 25 | 28 |
| Engine Instruments | 5 | 9 |
| Altimeter | 10 | 7 |
| Vertical Speed | 10 | 8 |
| Turn and Bank | 6 | 5 |

Three of these instruments are concerned primarily with the vertical axis; i.e., altimeter, vertical speed and gyro horizon. It is assumed that in a normal pilot scan of the aircraft's instruments, the three instruments will provide information in about the same ratio as in the eye movement studies. The average fixation time on each instrument will be dependent upon the nature of the information to be obtained and the type of display being used. This time can be predicted from experimental evidence and from the use of information theory. With information theory it is possible to determine the number of bits of information contained in the reading. Since rates of information absorption by man are known, typical reading times can then be obtained.

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* Eye Fixations of A/C Pilots, IV. Frequency, Duration and Sequence of Fixations during Routine Instrument Flight. ASTIA No. 73422 Jones, Milton and Fitts, March 1950.

A realistic "on" time can be determined by computing the mean fixation time if the reading time of each of our aircraft's instruments will be weighted by the WADC eye movement use frequency. For three instruments this "on" time would be determined by:

$$\bar{t}_{on} = \frac{n_1 t_1 + n_2 t_2 + n_3 t_3}{n}$$

where $\bar{t}_{on}$ = mean reading time for all vertical instruments

$n_1, n_2, n_3$ = number of uses per minute as determined by WADC eye movement studies (for each instrument)

$t_1, t_2, t_3$ = reading times of aircraft instruments as determined by information analysis

$$n = n_1 + n_2 + n_3$$

This mean reading time is then used to recompute the actual percent viewing time necessary for maximum control. Since transitions between instruments are not considered in this analysis a figure must be added to the axis for this purpose for the multiple instruments.

The result of the new percentage time is a hypothetical instrument which is a composite of the instruments in the aircraft. It is to be noted that the $\bar{t}_{on}$ computation is a corrective measure. The use of the WADC data only provides a small corrective factor which will not affect the results greatly even if a fairly large difference is present.

A comparison of the aircraft instruments in the lateral axis and those used in the experimental determination are information-wise the same. The two principle instruments of lateral information, the Flight Director-Attitude Indicator and integrated heading display are located adjacent to one another vertically and display information of the same order of difficulty as the experimental situation. Command heading changes will be analyzed separately since the experiment dealt with holding heading while using bank angle information.

## Vertical Axis Analysis

The purpose of the experiment is to provide a means of determining the relative amount of time a pilot must spend to exercise maximum control of the vertical axis. The basis for this determination will be a figure of merit which we call "percent viewing time" and is defined empirically in the experiment. Figure 9 is a block diagram of the experimental situation. The aircraft's vertical axis with damper engaged is simulated by the analog computer as in Figure 10. Aircraft flight path angle is summed with a

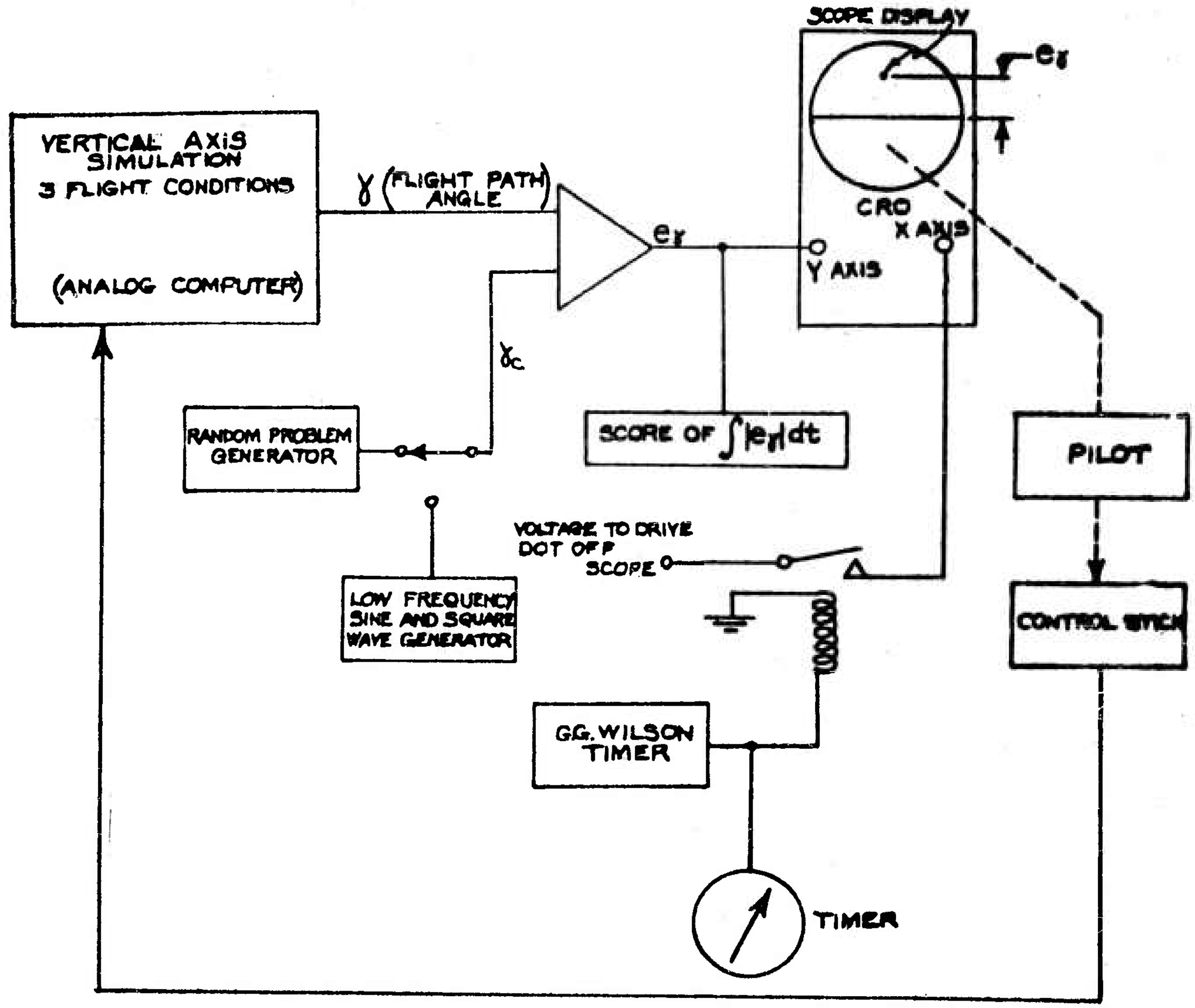


Figure 9. Vertical Axis Analysis Experimental Block Diagram

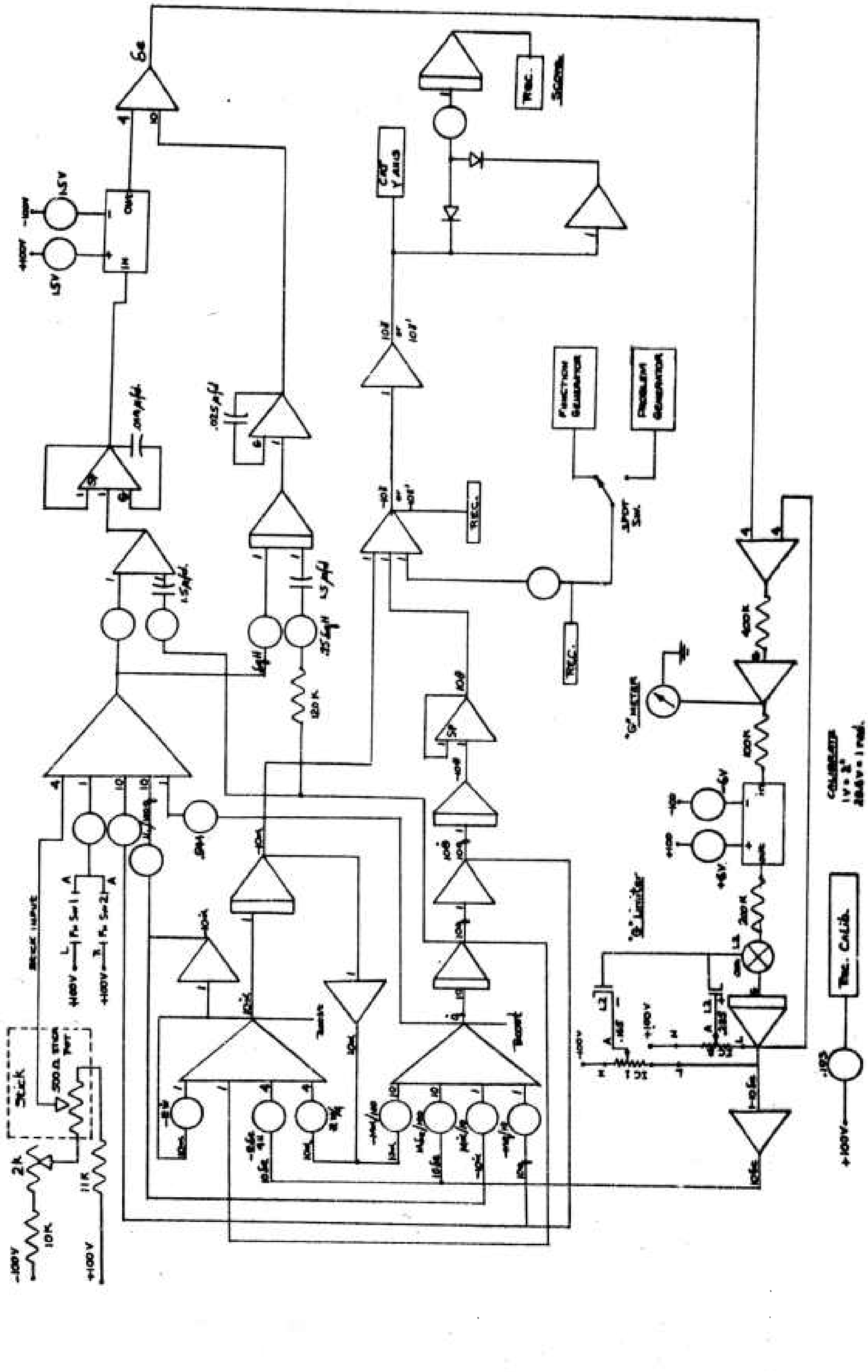


Figure 10. Pilot Workload Analysis - Vertical Axis

command signal to develop an error signal which is fed to an oscilloscope display or "error dot." No lateral problem was present in this experiment. The dot could be made to instantaneously disappear by means of applying a voltage to the x-axis of the scope. This x-axis voltage was precisely cycled on and off by an electronic "G. G. Wilson" timer which was adjustable in both on and off time. To the pilot, the error dot appeared when no voltage was applied to the x-axis and disappeared on its application. The "percent experimental viewing time" is then defined by measuring the on-off cycling of the G. G. Wilson timer.

$$\% \text{ exp viewing time} = \frac{\text{time dot present}}{\text{time dot off scope}}$$

This empirical value is later modified in order to allow adaptation to the aircraft cockpit.

The pilot was instructed to "null" the error dot at all times. The degree to which he was able to perform this was scored on the computer by integrating the absolute value of the difference between command and actual flight path.

$$\text{Score} = K \int |e_{\gamma}| \, d\,t$$

where $e_{\gamma} = \gamma_A - \gamma_c$

$K$ = constant

$\gamma_A$ = actual flight path angle $= \theta - \alpha$

($\theta$ = pitch attitude)

($\alpha$ = angle of attack)

$\gamma_c$ = flight path command

Flight path angle was chosen as the control parameter since it is the best description of vertical axis behavior. Modern fire control and autopilot systems are examples of control systems built around this parameter. Even level flight is essentially a flight path problem since attitude must be cross checked with rate of climb to establish the flight condition.

The pilot was environmentally isolated by means of the Honeywell aircraft simulator cockpit where he introduced his commands into the airframe by means of a control stick. (See Figure 11.)

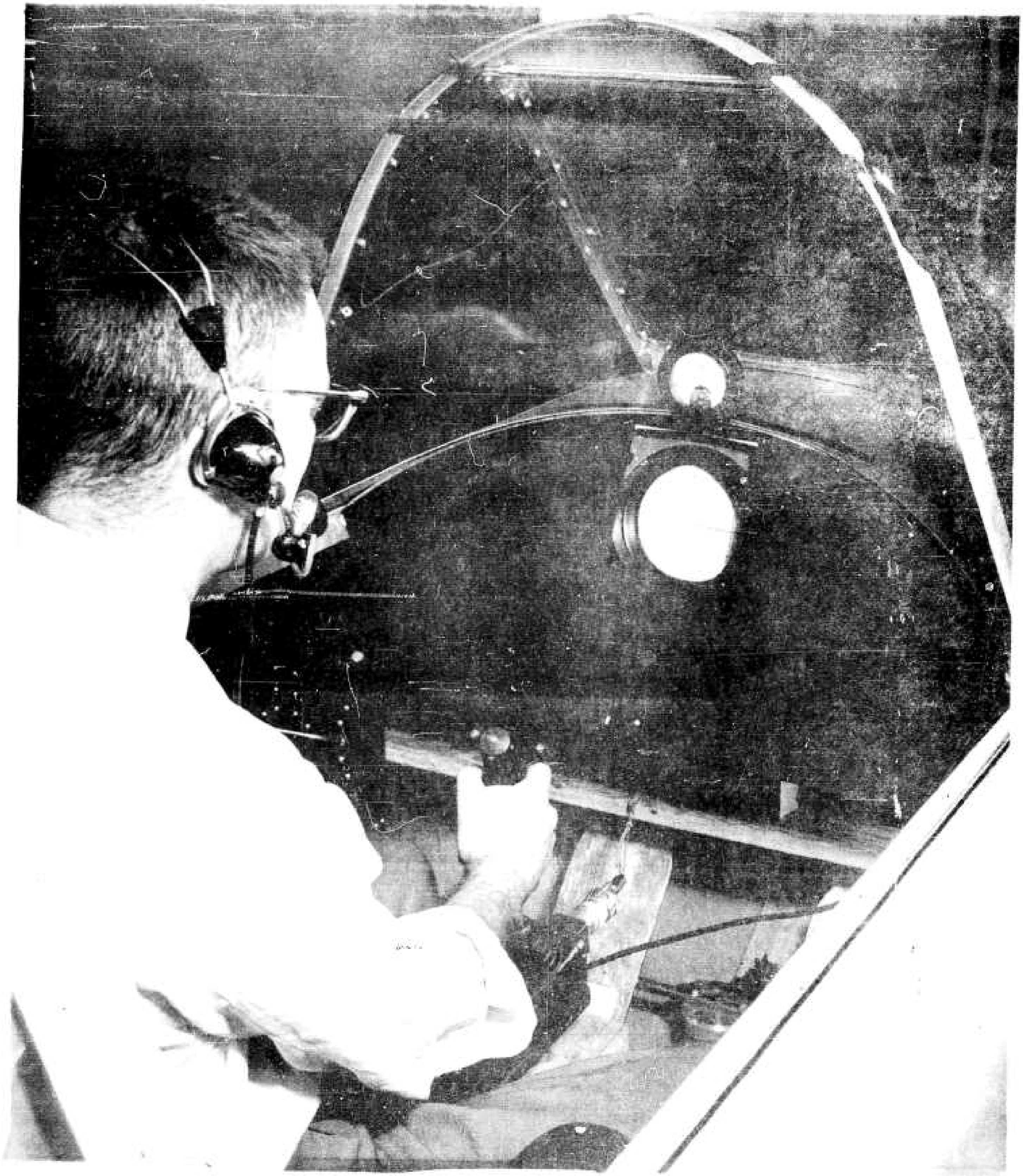

Figure 11. Honeywell Aircraft Simulator Cockpit

The simulation of flight as shown in Figure 10 was used to simulate three flight conditions:

Mach X, sea level
Mach Y, $Y_1$ feet
Mach Z, $Z_1$ feet

This simulation was obtained from the autopilot analysis group which designed the aircraft's dampers. Since their work has been recently substantiated by flight test, it is felt that it will represent the system.

Due to a tendency to initially overcontrol in some flight condition, a "g" meter was included in the cockpit for orientation purposes. The "g" limiter of the damper prevents damage to the airframe, but computer overloading occurred when the pilot persisted in trying to pull too many "g's".

Experimental Procedure:

A number of preliminary experiments were necessary to establish a meaningful experiment. With step inputs, it was found that the pilot could adapt his transfer function with practice so that an analysis was not possible. With practice the pilot would sometimes enter the loop with accurate memory and an integrating capability, both of which proved extremely variable. A technique was developed which was based upon a maximum contribution by the pilot to the control problem. It is assumed that the pilot will be required to precisely fly to the best of his ability. In order to do this, a forcing function was chosen experimentally to be a moderately difficult task when the pilot had a continuous view of the problem. The nature of the problem was natural to the experimental pilots who seemed to consider the aircraft undergoing gusty weather conditions. The forcing function signal originated from two sources; a random low frequency signal source and a low frequency oscillator. The pilot was never informed of the nature of the signals which were interchanged to prevent learning the problem. Scores were kept of behavior on both the random and sinusoidal signals although only the results of the sine-wave input is reported in this report. By hiding the sine signal amidst the random signals it was possible to use a more precise relationship which could yield consistent results.

Six experienced pilots were used in the experiment. Each received instruction concerning the job and then was given a controlled practice session. Typical step inputs which were included in the practice period are shown in Figure 12.

Although the damper configuration is compensated for airspeed changes, the aircraft is more difficult to control at the lower speed conditions. The general response characteristics of the man machine furnished a clue to the type of forcing function we could expect the pilot to control. Practice was also given on the on-off cycle control.

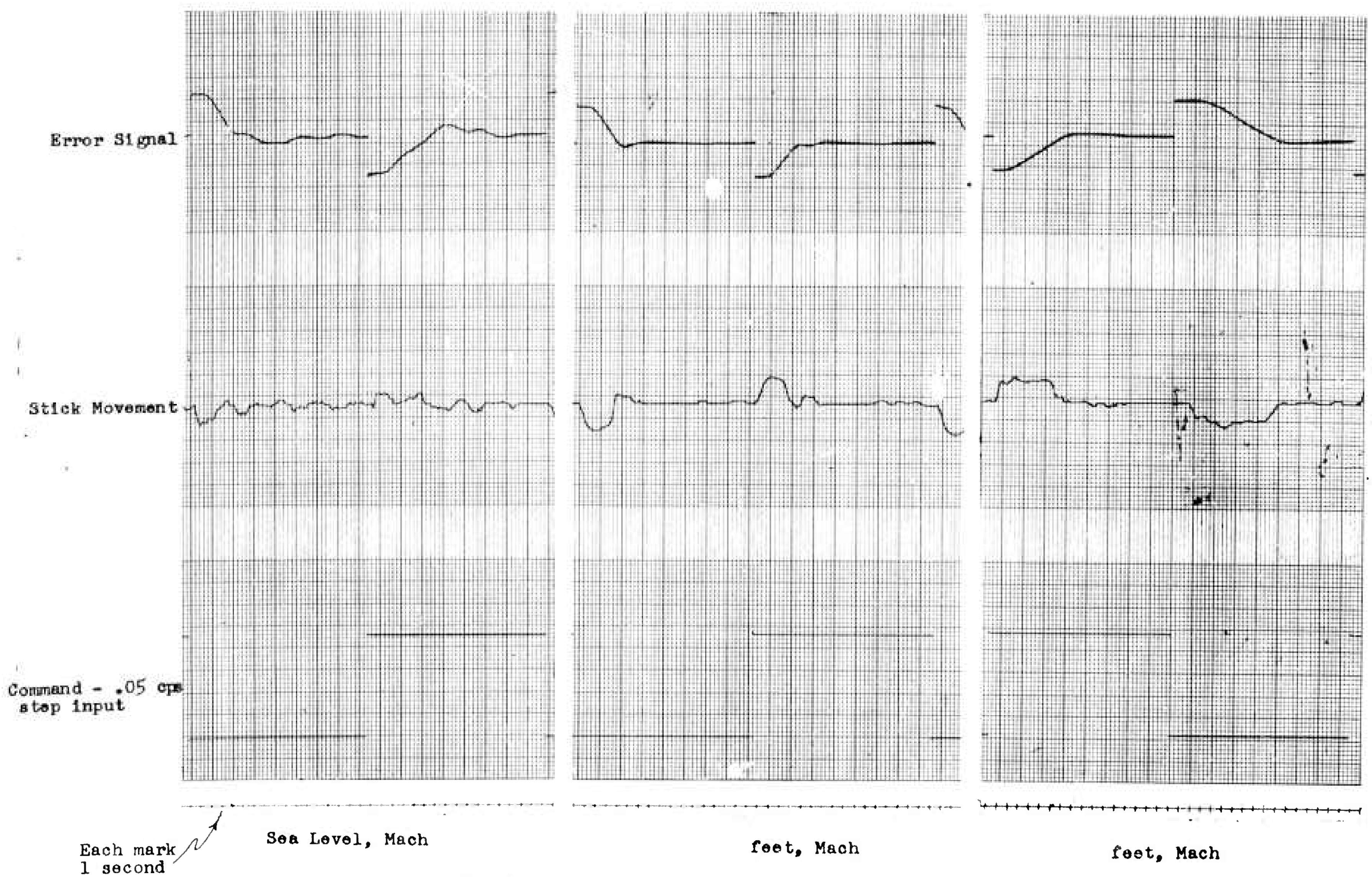


Figure 12. Typical System Responses for Step Inputs.

The official experiment began with the pilot controlling the system with a continuously "on" display, or a 100 percent viewing time. Three evaluation periods were obtained for each viewing percentage. The on-off cycling then began. An "on" time of 0.25 second was determined experimentally to be an adequate stimuli which was long enough to observe the direction, displacement and obtain some rate information about the error. This time was sufficient for the pilot to react to its presence and determine a corrective action. The off-time was then varied so that various percentages of viewing time could be obtained. The percentages chosen were obtained from preliminary experiments which had indicated that a sharp break occurred in performance at a particular value.

Experimental Results:

Although differences exist between pilots, the general conclusion that pilots require a particular amount or rate of information input to best control the system was substantiated. It is interesting to note that several pilots did not do their best job of tracking under continuous conditions. It is felt that the general nature of the problem required a maximum output to obtain control and that the results are remarkably consistent considering the complexity of the measurement. Figure 13 is a sample of the information obtained from an experimental situation.

The data from the vertical axis was compiled and is summarized in Table 2. Figures 14, 15, and 16 are a plot of the overall mean for each flight condition and how each varies from the mean. Figure 17 summarizes the total experiment and is the basis for computing the actual pilot work load. In general, as "q" increases the pilot work load decreases and the amount of performance loss for a given decrease in percent viewing time is less.

## Lateral Axis Experimental Analysis

Experimental Procedure:

The procedure used in the vertical axis did not prove applicable to the lateral axis since the mission involves maintaining heading for the most part. To ask the pilot to follow a changing heading or constantly changing roll command lacked realism in principle or when experimentally investigated. Experience with high performance aircraft has indicated that maintaining heading is relatively easy at high speeds and altitudes. A realistic situation was obtained when the pilot was instructed to hold a heading while being subjected to typical wind conditions. The wind conditions were determined by experimentally setting up a sea level condition which seemed typical to several pilots and extrapolating from this to higher speeds and altitudes from known wind information.* Traces from flights in the

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* "Methods and Results of Upper Atmosphere Research," Geophysical Research Paper No. 43. ASTIA 101944 J. Kaplan, G. Schilling, H. Kallman, November 1955

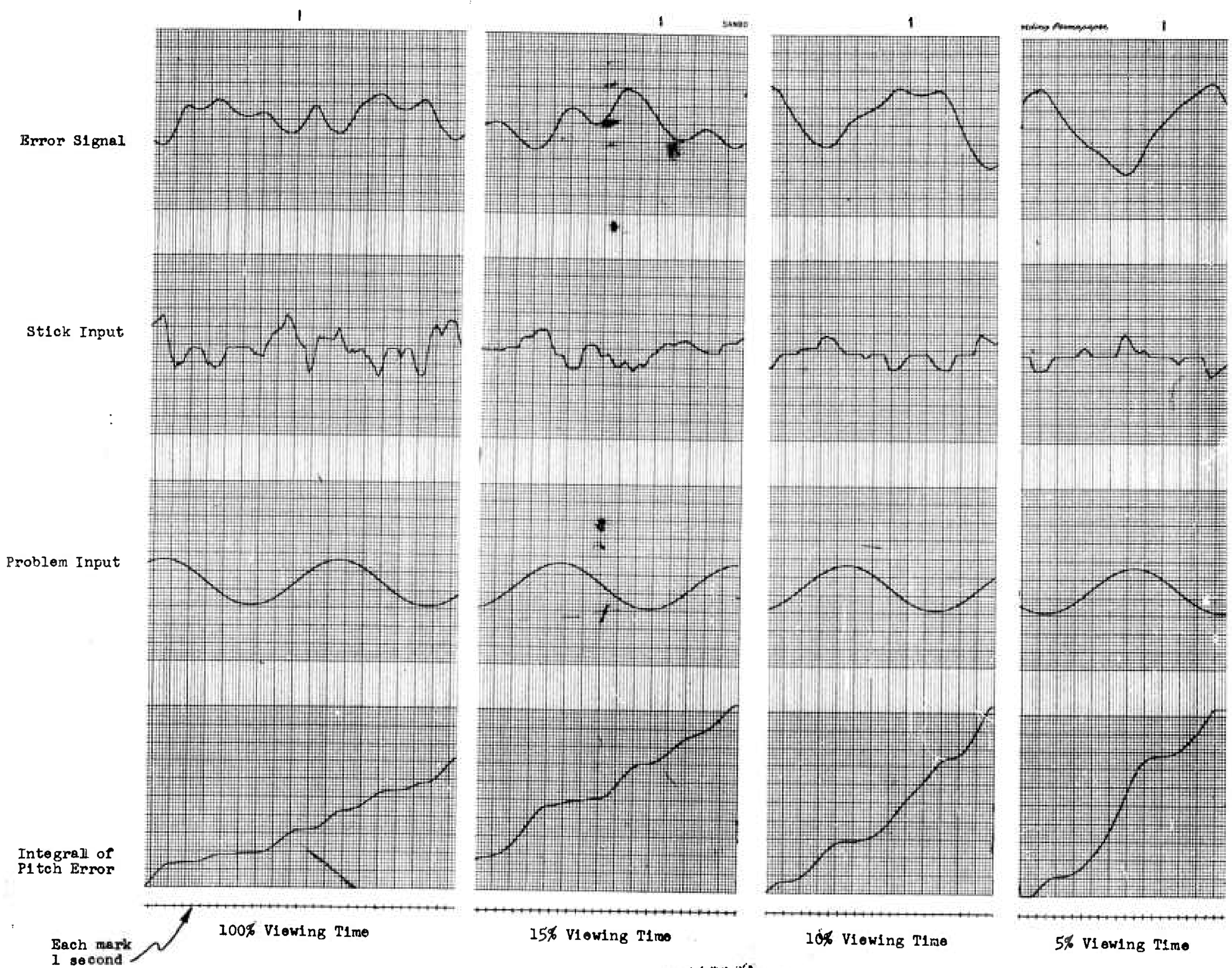


Figure 13. Typical Responses for Pitch Axis at Mach Feet

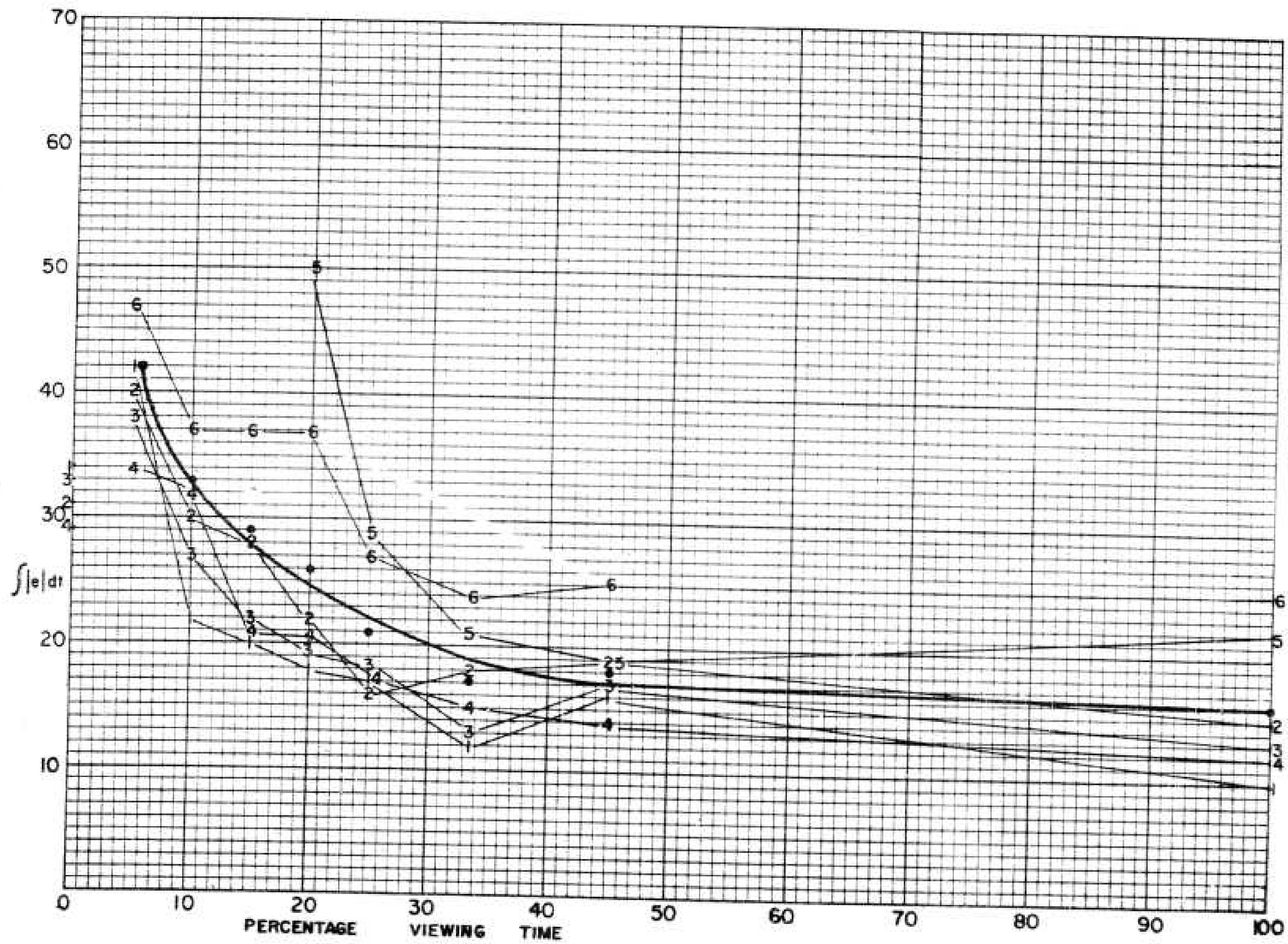


Figure 14. Flight Path Control versus Percent Pilot Viewing Time - Mach Feet

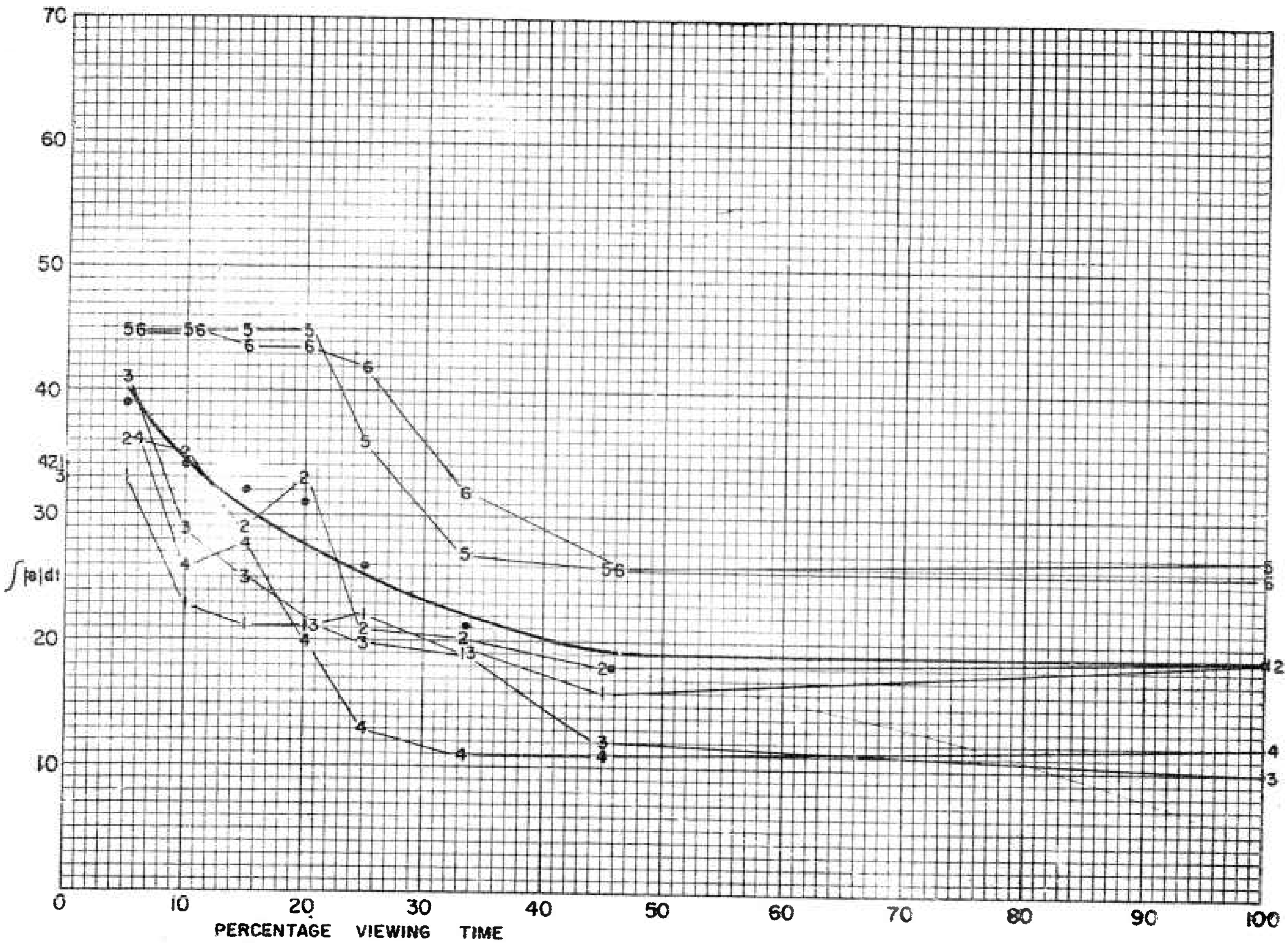


Figure 15. Flight Path Control versus Percent Pilot Viewing Time - Mach Feet

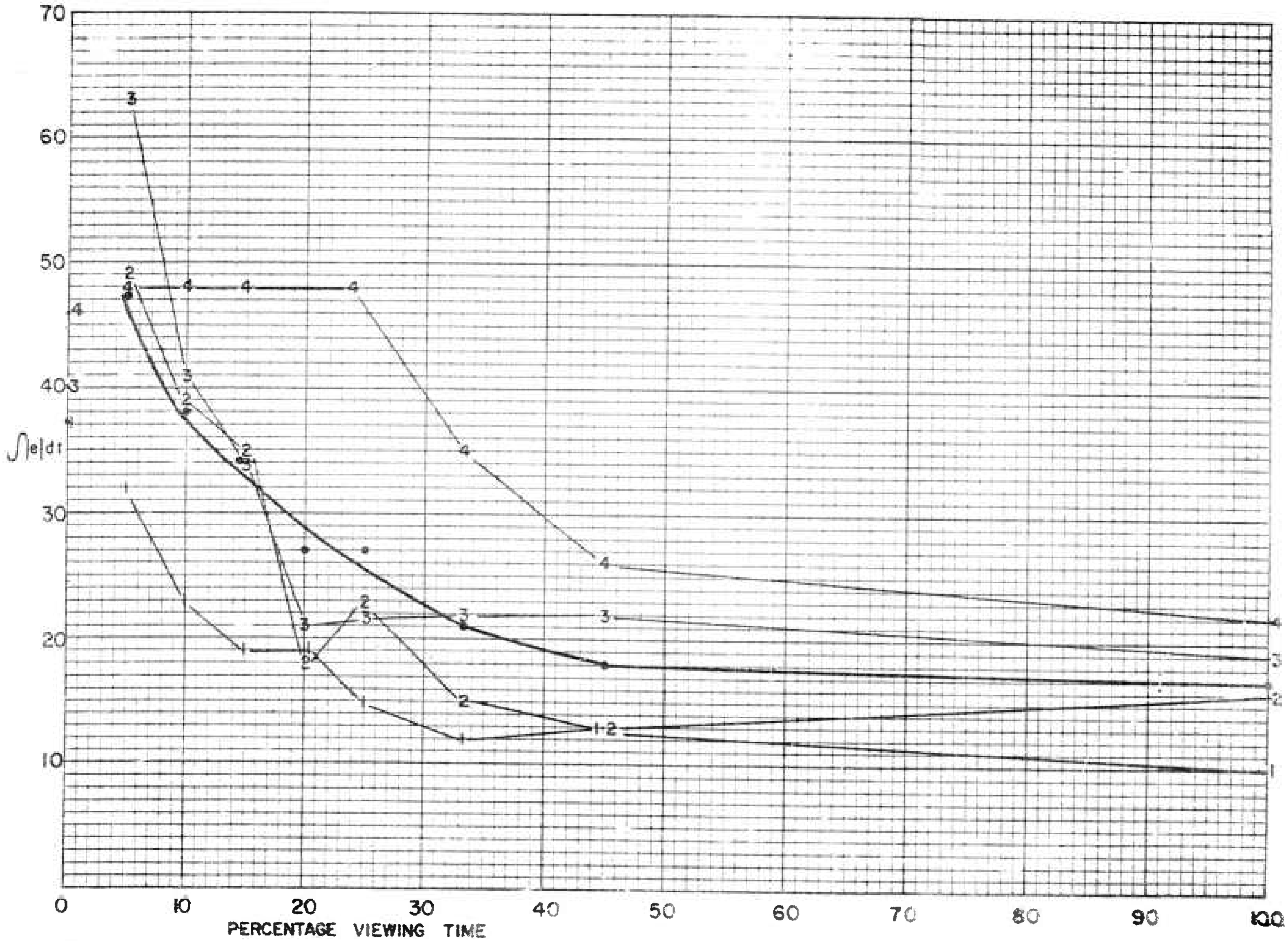


Figure 16. Flight Path Control versus Percent Pilot Viewing Time - Mach Sea Level

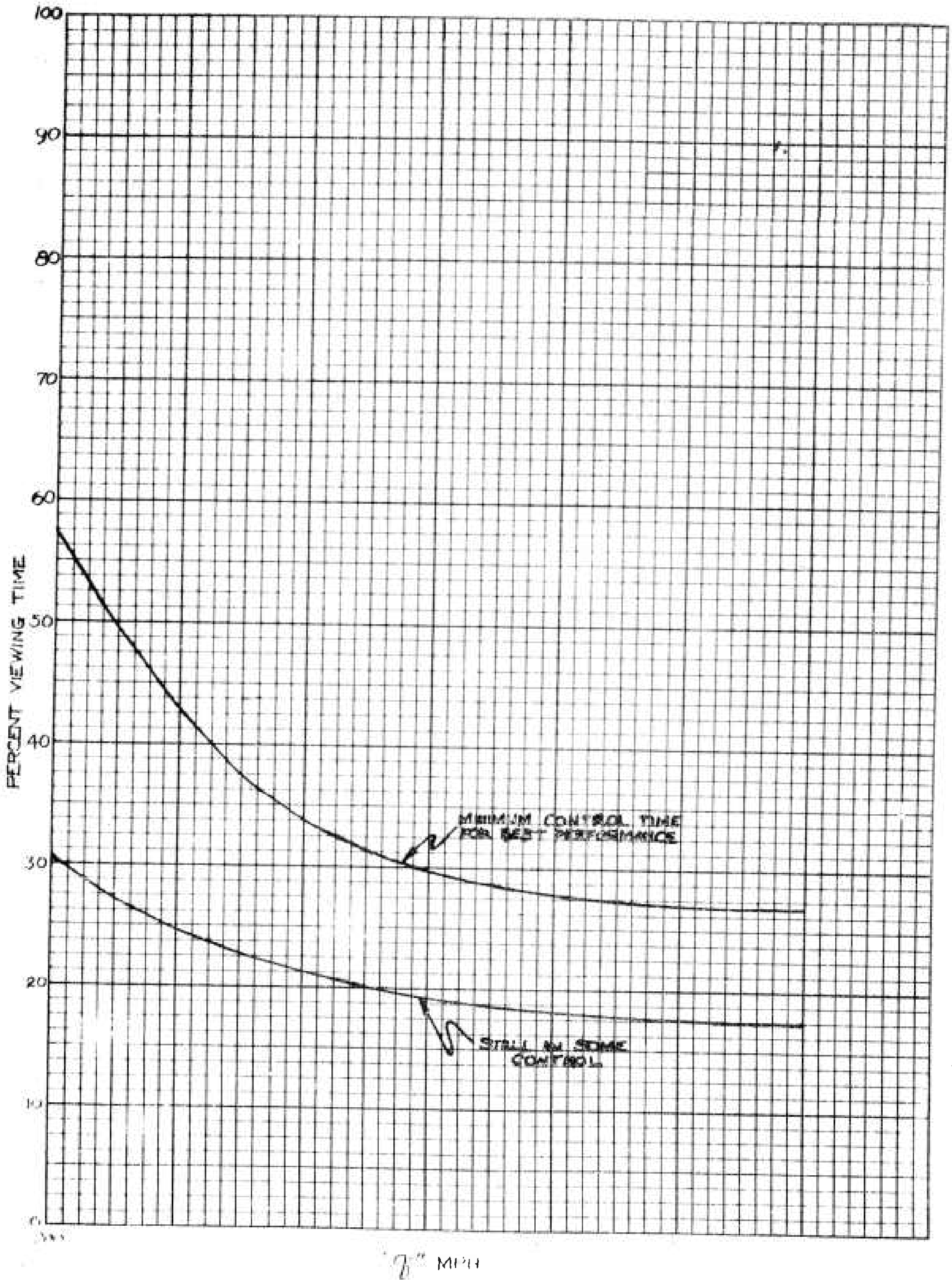


Figure 17. Flight Path Angle, Minimum Control Times

Table 2. Vertical Axis Scores (Mean Errors by Subjects)

| Percent Viewing | No. 1 | No. 2 | No. 3 | No. 4 | No. 5 | No. 6 | Mean |
|---|---|---|---|---|---|---|---|
| | | | (Mach | | | ft) | |
| 100 | 10 | 15 | 13 | 12 | 22 | 25 | 16 |
| 45 | 16 | 19 | 17 | 14 | 19 | 25 | 18 |
| 33 | 12 | 18 | 13 | 15 | 21 | 24 | 17 |
| 25 | 17 | 16 | 18 | 17 | 29 | 27 | 21 |
| 20 | 18 | 22 | 19 | 20 | 50 | 37 | 26 |
| 15 | 20 | 28 | 22 | 21 | - | 37 | 29 |
| 10 | 22 | 30 | 27 | 32 | - | 37 | 33 |
| 5 | 42 | 40 | 38 | 34 | - | 47 | 42 |
| | | | (Mach | | | ft) | |
| 100 | 19 | 19 | 10 | 12 | 27 | 26 | 19 |
| 45 | 16 | 18 | 12 | 11 | 26 | 26 | 18 |
| 33 | 19 | 20 | 19 | 11 | 27 | 32 | 21 |
| 25 | 22 | 21 | 20 | 13 | 36 | 42 | 26 |
| 20 | 21 | 33 | 21 | 20 | 45 | 44 | 31 |
| 15 | 21 | 29 | 25 | 28 | 45 | 44 | 32 |
| 10 | 23 | 35 | 29 | 26 | 45 | 45 | 34 |
| 5 | 23 | 36 | 41 | 36 | 45 | 45 | 39 |
| | | | (Mach | | Sea Level) | | |
| 100 | 10 | 16 | 19 | 22 | | | 17 |
| 45 | 13 | 13 | 22 | 26 | | | 18 |
| 33 | 12 | 15 | 22 | 35 | | | 21 |
| 25 | 15 | 23 | 22 | 48 | | | 27 |
| 20 | 19 | 18 | 21 | 48 | | | 27 |
| 15 | 19 | 35 | 34 | 48 | | | 34 |
| 10 | 23 | 39 | 41 | 48 | | | 38 |
| 5 | 32 | 49 | 63 | 48 | | | 48 |

simulator corresponded to the Goodyear simulator data which was aimed at determining typical wind conditions. The best indication of the realism of the problem is by comparing pilot stick movements in the simulator and the recording of stick movements during initial flight tests of the aircraft. (See Figure 18.) Since the control of heading and roll are so interdependent with the pilot controlling roll to maintain heading, both indications were used in the experiment. Heading error was presented on the x-axis of the scope. Each experiment began on the desired heading and proceeded with the pilot maintaining this heading in the face of the gusty conditions. Bank angle was presented on a meter movement directly below the heading error indicator. Since an additional indicator was to be read, a new "on" time had to be established by experiment. Several pilots found 0.5 second as a satisfactory exposure time to handle both instruments. It was not possible to use the previous technique in controlling the display "on-off" cycle because of the meter movement. A post-type light was used to illuminate the bank scale. The "on" cycle then turned on both the light and the heading error dot on the scope.

A procedure similar to that used in the vertical axis was then followed. Each pilot was given practice in handling the system as shown in Figure 19. Each flight condition was then investigated with decreasing experimental viewing percentages. Since a realistic problem input was used, it is possible to score pilot performance in terms of mean heading error.

$$\bar{e}_H = \frac{\int_0^T |e_H| \, dt}{T}$$

$T$ = total time

$e_H$ = heading error

$\bar{e}_H$ = mean heading error

Experimental Results:

Table 3 is a summary of the data obtained experimentally from seven experienced pilots. The mean values for the three conditions is plotted in Figures 20, 21 and 22. The data in this case proved to be very consistent for each pilot and uniform among pilots.

A typical trial is shown in the computer traces of Figure 23.

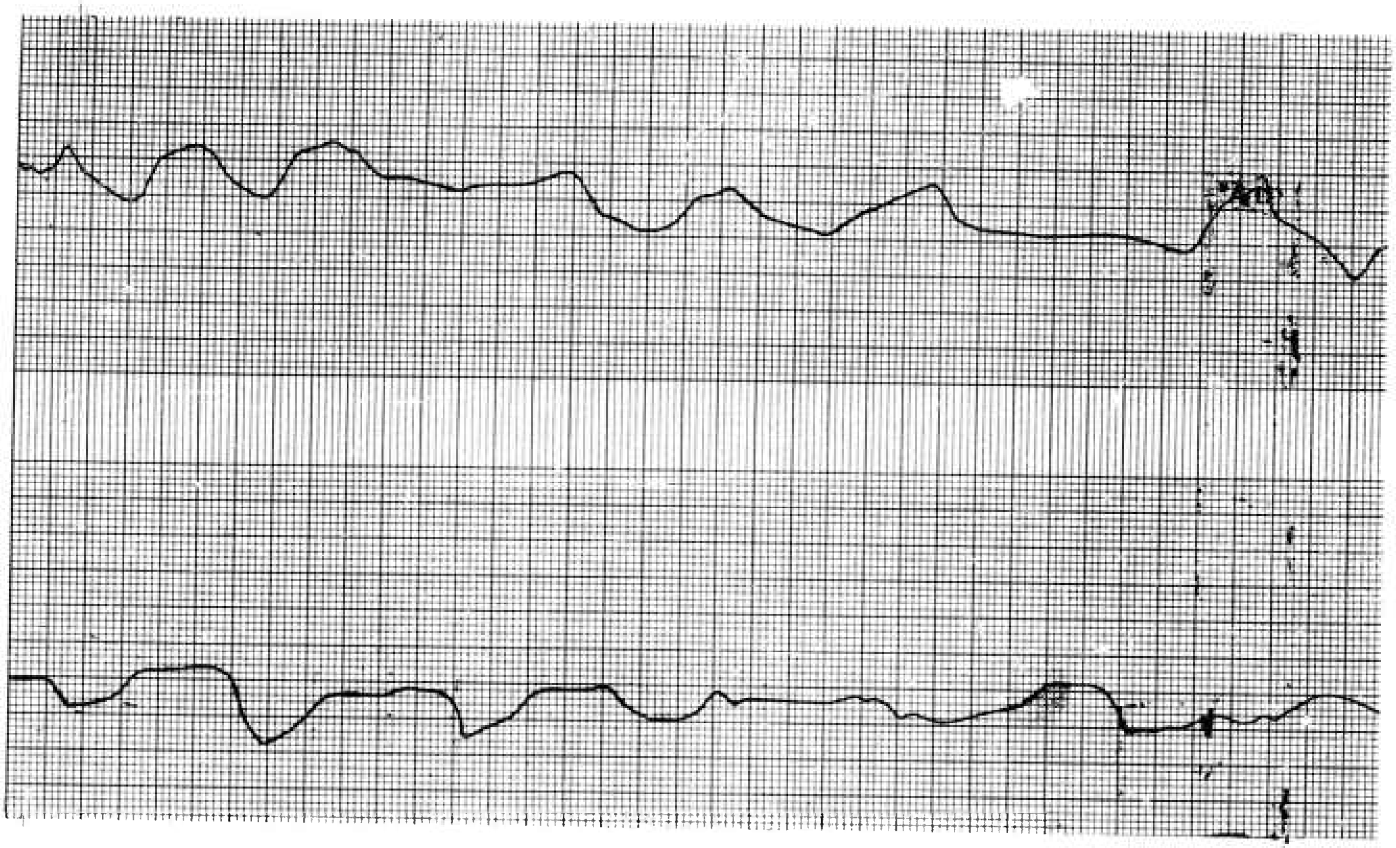

Figure 18. Comparison of Flight Test and Evaluation

1. flight test. Aileron deflection. 185 knots, 14,000 ft., damper on.

2. Experimental stick roll input.

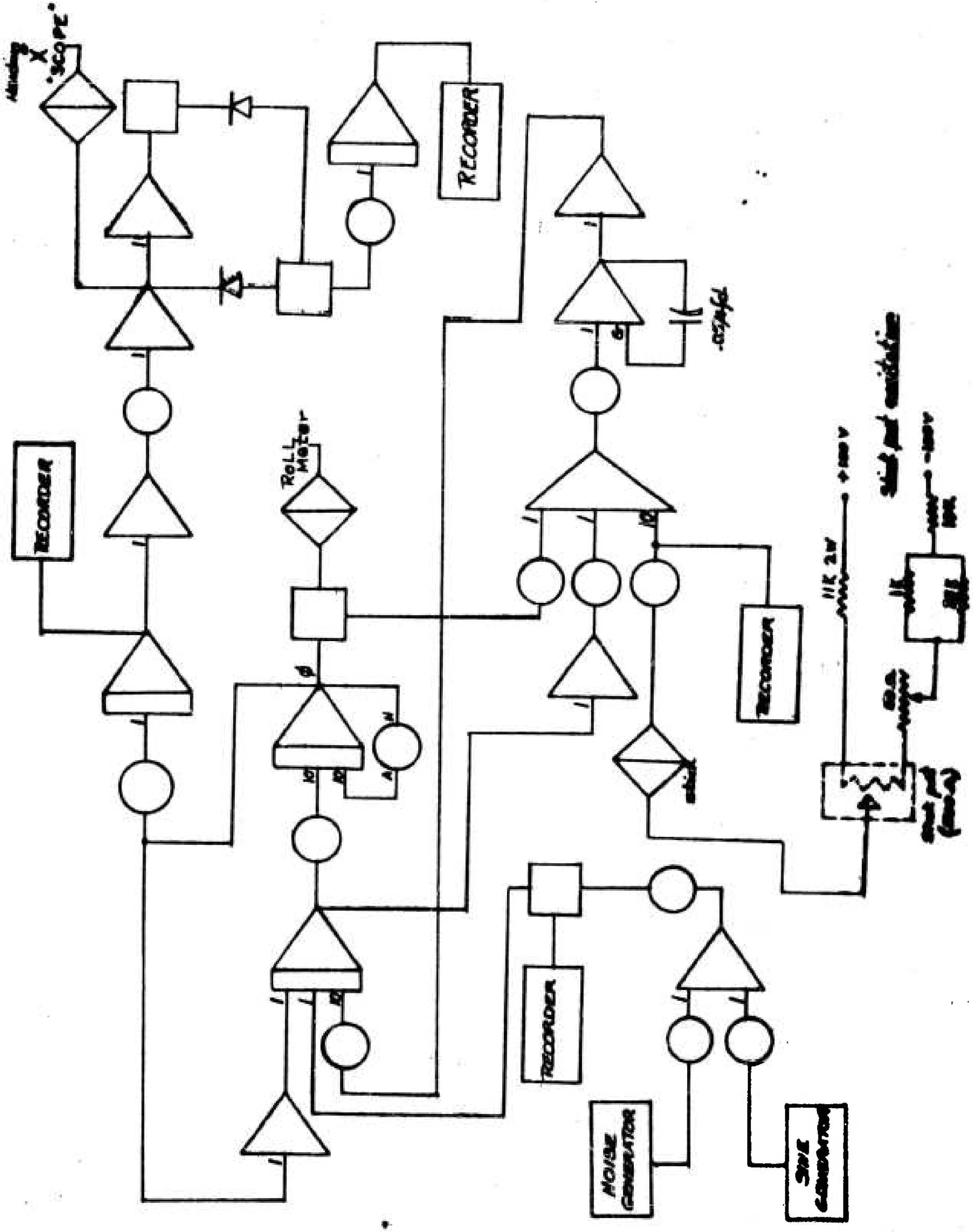


**Figure 19. Minimum Pilot Workload Roll Simulation**

**Table 3. Lateral Axis Scores (Mean Heading Error by Pilot)**

| Percent Viewing | No. 1 | No. 2 | No. 3 | No. 4 | No. 5 | No. 6 | No. 7 | Mean |
|---|---|---|---|---|---|---|---|---|
| | | | (Mach ft) | | | | | |
| Cont. | 0.03 | 0.06 | 0.06 | 0.02 | 0.05 | 0.08 | 0.03 | 0.05 |
| 50 | 0.07 | 0.08 | 0.09 | 0.05 | 0.08 | 0.14 | 0.04 | 0.08 |
| 40 | 0.09 | 0.11 | 0.15 | 0.05 | 0.10 | 0.16 | 0.05 | 0.09 |
| 30 | 0.07 | 0.17 | 0.14 | 0.06 | 0.25 | 0.16 | 0.05 | 0.13 |
| 20 | 0.13 | 0.20 | 0.12 | 0.07 | 0.35 | 0.35 | 0.07 | 0.18 |
| 15 | 0.17 | 0.19 | 0.14 | 0.07 | 0.39 | 0.51 | 0.13 | 0.23 |
| 10 | 0.28 | 0.28 | 0.22 | 0.13 | 0.55 | 0.62 | 0.22 | 0.33 |
| 5 | 0.35 | 1.40 | 0.35 | 0.55 | - | 0.62 | 0.35 | 0.60 |
| 0 | | | | | | | | |
| | | | (Mach ft) | | | | | |
| Cont. | 0.12 | 0.15 | 0.11 | 0.08 | 0.10 | 0.18 | 0.07 | 0.12 |
| 50 | 0.14 | 0.23 | 0.16 | 0.14 | 0.23 | 0.25 | 0.10 | 0.18 |
| 40 | 0.17 | 0.20 | 0.13 | 0.14 | 0.31 | 0.34 | 0.10 | 0.20 |
| 30 | 0.19 | 0.40 | 0.14 | 0.12 | 0.50 | 0.61 | 0.13 | 0.30 |
| 20 | 0.24 | 0.40 | 0.21 | 0.15 | 0.49 | 0.91 | 0.14 | 0.36 |
| 15 | 0.38 | 0.61 | 0.32 | 0.28 | 1.30 | 1.25 | 0.16 | 0.61 |
| 10 | 0.49 | 2.40 | 0.60 | 0.46 | 2.30 | - | 0.55 | 1.31 |
| 5 | 0.85 | - | 3.90 | 1.10 | - | - | 0.78 | 1.66 |
| 0 | | | | 1.80 | | | | |
| | | | (Mach , Sea Level) | | | | | |
| Cont. | 0.28 | 0.35 | 0.42 | 0.20 | 0.38 | 0.54 | 0.22 | 0.34 |
| 50 | 0.48 | 0.51 | 0.54 | 0.43 | 0.92 | 0.82 | 0.27 | 0.57 |
| 40 | 0.57 | 0.67 | 0.59 | 0.41 | 0.77 | 1.04 | 0.32 | 0.62 |
| 30 | 0.94 | 0.80 | 0.72 | 0.53 | 1.40 | 1.94 | 0.47 | 0.97 |
| 20 | 1.54 | 1.76 | 1.10 | 1.67 | 2.40 | 2.80 | 0.59 | 1.69 |
| 15 | 1.83 | 1.85 | 2.40 | 0.68 | 2.60 | - | 0.71 | 1.85 |
| 10 | 3.14 | - | - | - | - | | 2.78 | 2.96 |
| 5 | | | | | | | | |
| 0 | | | | | | | | |

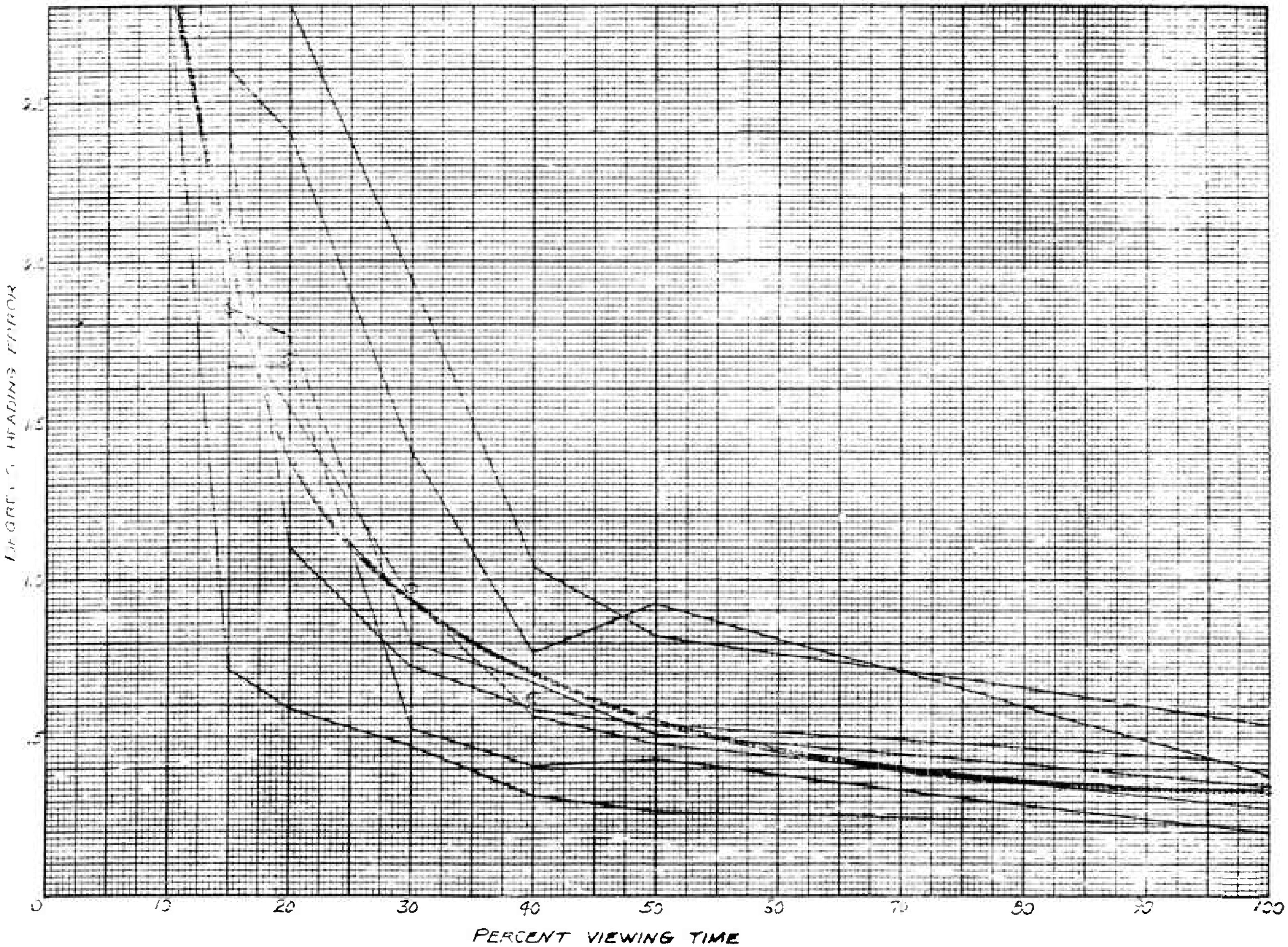


Figure 20. Lateral Axis Mean Heading Error versus Percent Pilot Viewing Time - Mach Sea Level

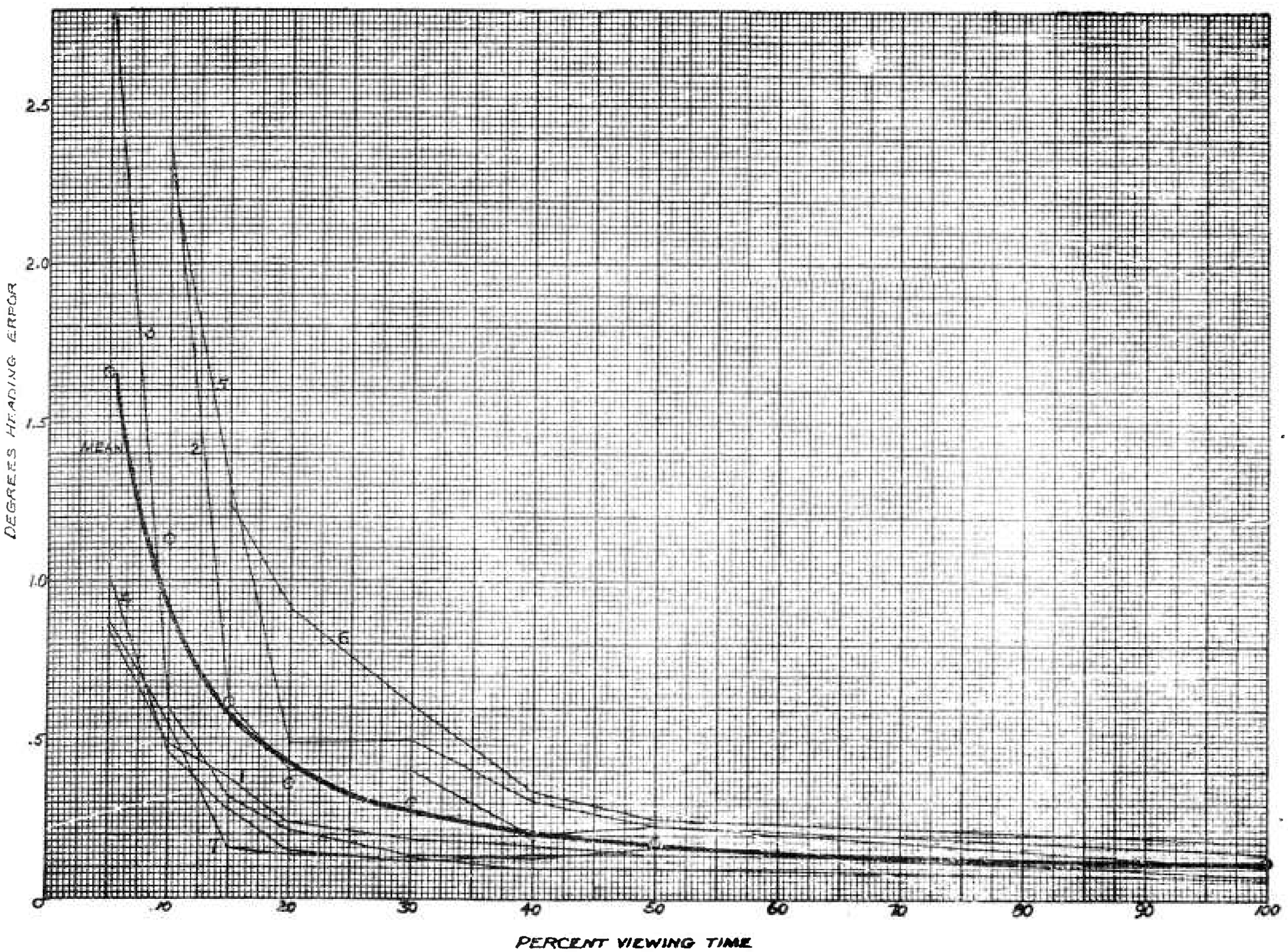


Figure 21. Lateral Axis Mean Heading Error versus Percent Pilot Viewing Time -
Mach Feet

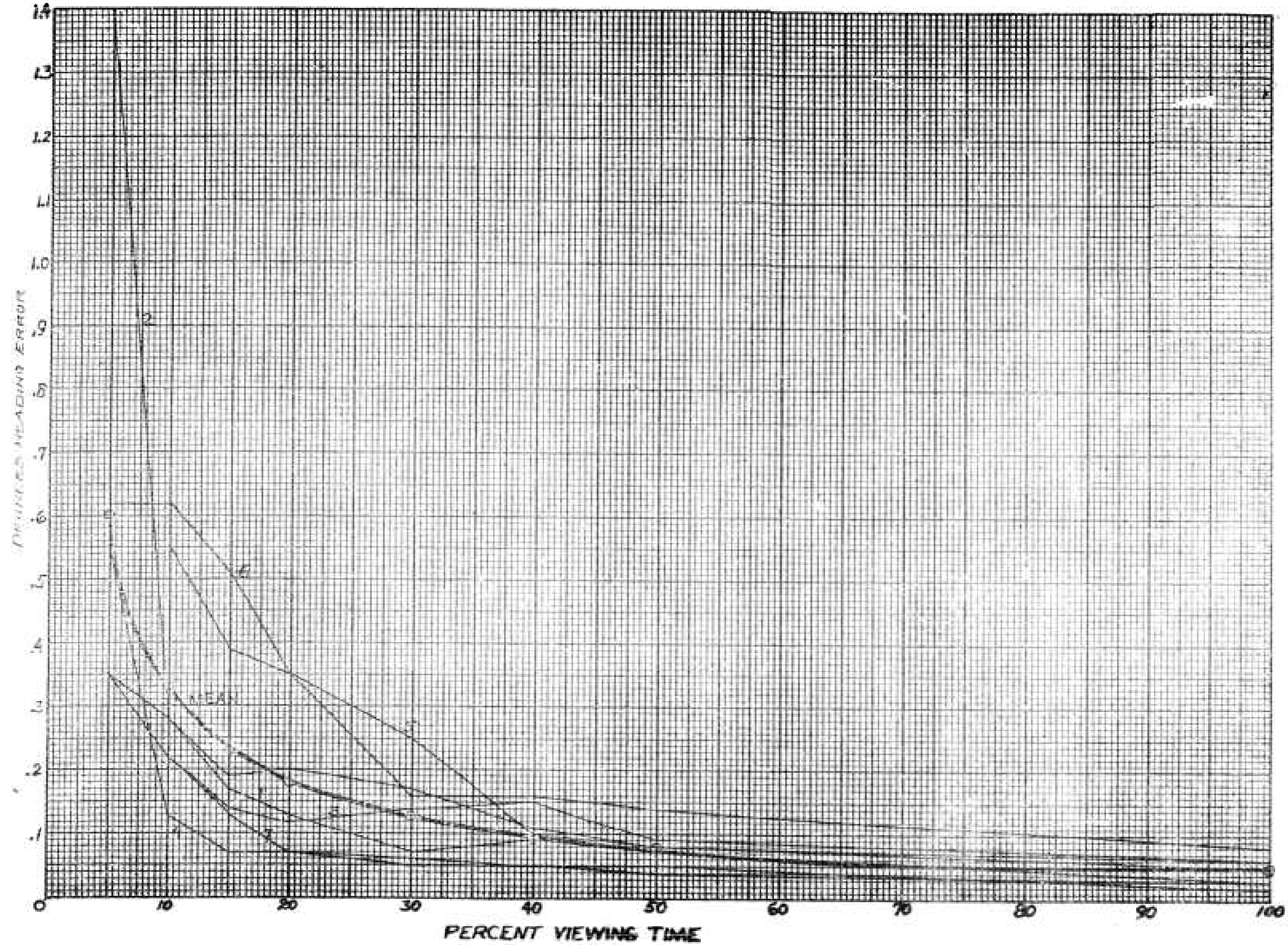


Figure 22. Lateral Axis Mean Heading Error versus Percent Pilot Viewing Time -

Mach Feet

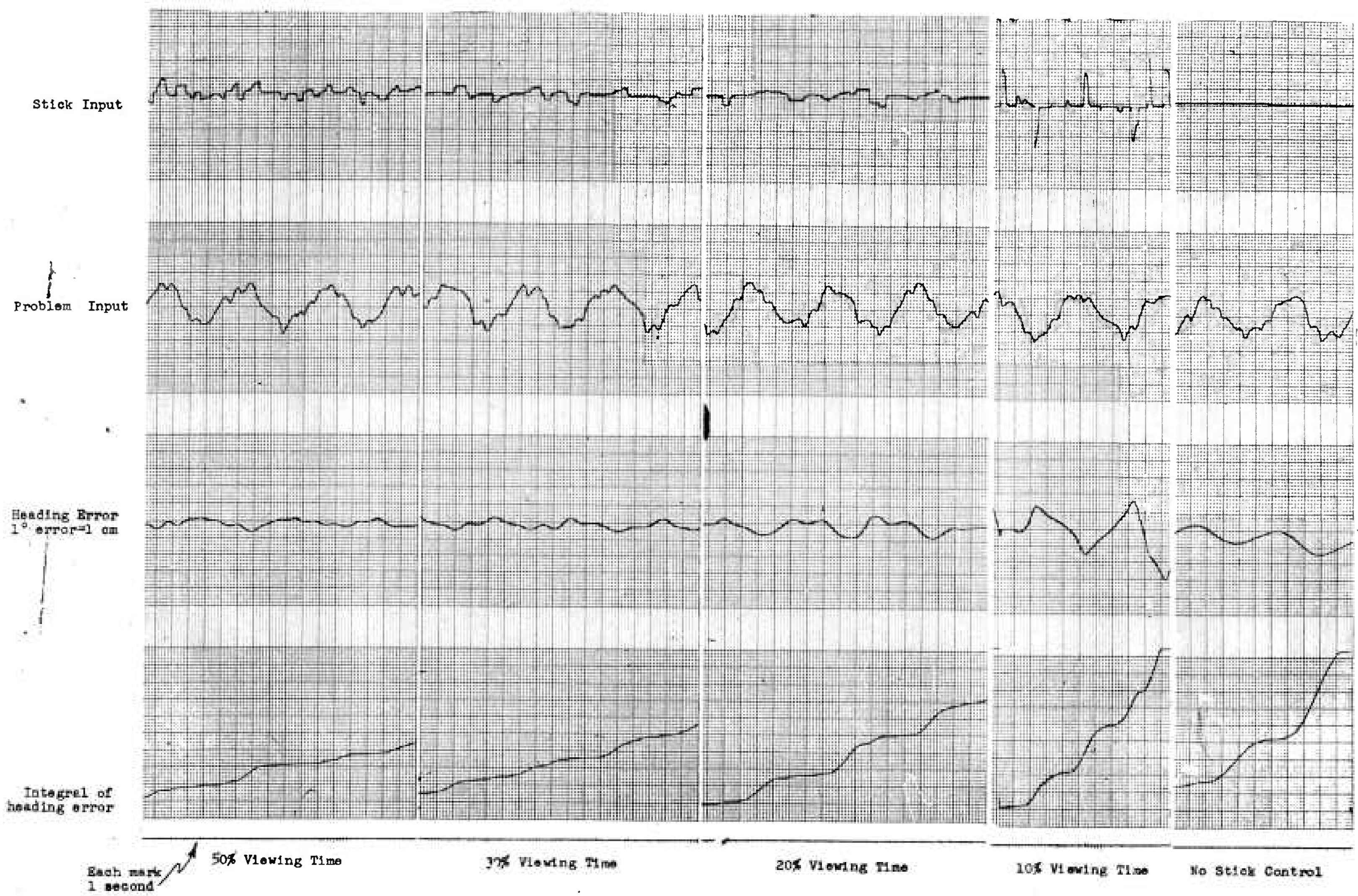


Figure 23. Typical Responses for Lateral Axis at Mach Feet

## G. RESULTS OF WORKLOAD ANALYSIS

**Method**

The information obtained from Sections B through F can be used to determine the pilot work load in terms of his maximum capability. Every effort was made to make a complete accounting of all the equipment and mission requirements. A study was made of all cockpit switches and their probable time of use. Broadcast control, using dampers only, was chosen for analysis since it required the highest pilot contribution and also represented a typical operational procedure. The mission chosen is a maximum effort attack with a minimum time from scramble to takeoff. An identification pass was included.

The initial analysis made no attempt to distribute work load from crowded moments to free ones. Those aspects of the pilot's operation which could be shifted to other less crowded moments were then transferred. This represents a skilled, well-trained operator handling the mission and aircraft. The requirements of the mission are met by this analysis in an effective manner. The pilot is in firm command of the mission and is maintaining precise control of his airframe to the commands of GCI and his equipment.

A question can be raised as to the accuracy of our final result. Every effort has been made to make the analysis conservative. It is felt that the analysis is representative of a highly trained, competent pilot operating at his highest level with equipment which is functioning correctly.

The analysis of Sections B through F indicated that the following aspects of the high performance attack mission were the most crowded for the pilot.

0 - 6 minutes - scramble to attaining Mach Z, $Z_1$ feet

9 - 17 minutes - search to break away from attack

The other time periods appeared to be well within the capability of the pilot as can be judged from relative work load and present operational requirements. The analysis was then broken into three sections:

Vertical axis

Lateral axis

Subsystems and miscellaneous

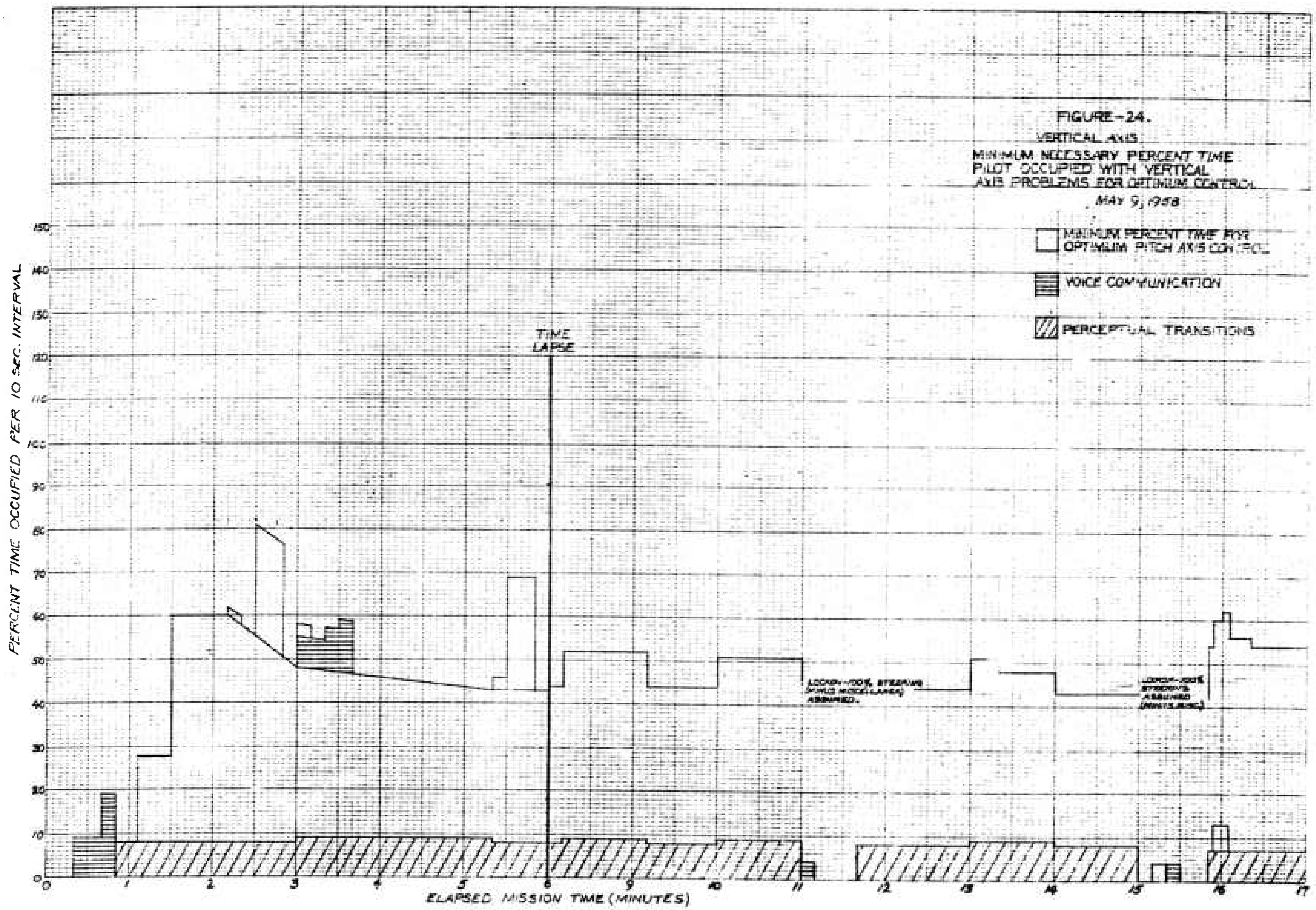


Figure 24. Vertical Axis - Minimum Necessary Percent Time Pilot Occupied with Vertical Axis Problems for Optimum Control

## Vertical Axis

Figure 24 is a plot of pilot work load associated with the vertical axis. Voice communications are conducted during the first minute to establish the GCI mission inputs to the aircraft. Better information is received after the aircraft is airborne during the fourth minute. The aircraft transmits information concerning the bogey at eleven minutes and during the 16th minute. Information theory was used to compute the work load associated with this communication. This process was described in Section E.

The perceptual transition percentage was computed on the basis of the number of instruments in the Phase I cockpit and the probable type of scanning as determined by the WADC eye fixation studies. The percentages change slightly with each general type of maneuver. It was assumed that pilot would not scan instruments during lock-on. (Min. 12 and 16).

Continuous vertical work load dependent upon stick control was predicted by using the percentages of minimum viewing time as found in Section F. The following is an example of the calculation.

(1) Time: 5 minutes, 20 seconds. Aircraft at Mach Z, $Y_1$ feet.

(2) Experimental value Mach Z, $Z_1$ feet = 27 percent.

(3) Calculation of Aircraft percentage: (See Section F.)

$$\bar{t}_{on} = \frac{(12)(0.47) + (6)(0.32) + (14)(0.26)}{12 + 6 + 14}$$

$$\bar{t}_{on} = 0.35 \text{ second}$$

$$\bar{t}_{off} = 0.675 \text{ second}$$

$$\% \text{ time} = \frac{0.35}{0.35 + 0.675} = 34 \text{ percent}$$

This value is then the primary value for control. Transistions requiring added instrument readings (ex "g" indication) and leveling out at precise altitude are added to this primary value, i.e. ($2^m$, $30^s$, $5^m$, $9^m$, $20^s$, $10^m$, $13^m$, $16^m$, $10^s$).

## Lateral Axis

Figure 25 is a plot of pilot work load associated with the lateral axis. A process similar to that used in the vertical axis simulation was used. An informational analysis of the basic problem indicated that the lateral axis instrumentation used in the experiment corresponded to that found in the aircraft cockpit. The experimental percentage values were therefore directly applied to the work load analysis.

A number of critical points in lateral control occur in the mission. The two turns at offset points ($9^m$ and $14^m$ $15^s$) must be accurately executed for mission success. Setting up the IDD at $1^m$ $50^s$ also adds work at crucial time.

In general, it is felt that maintaining heading to within a degree will be a relatively easy job. The work load magnitude in performing turning maneuvers was established theoretically. A more sophisticated computer configuration would be necessary to determine this experimentally.

## Miscellaneous Subsystems

Figure 26 is a plot of all pilot work load for such factors as armament, communication, lighting and speed control. The values for this category are derived directly from the informational analysis of Section E. Engine and fuel monitoring are included in this analysis. The placement of tasks on the time scale has been changed from that originally developed in the second-by-second analysis in order to distribute the work load into more desirable proportions.

## Total Work Load

Figure 27 is a plot of the total pilot work load. Theoretically, 100 percent is the maximum load a pilot is capable of, however, each pilot will have his own ceiling which will be somewhere near the theoretical value. The extent of this individual variation is not known although estimates can be made on the basis of various experiments.

A second aspect of the work load is the amount of time a man can operate at top efficiency. Probably a man can work at full capacity for only a limited amount of time. Extended high work loads will result in lowering the capability of the operator and thus decreasing system performance.

From Figure 27 it would appear that the initial 3.5 minutes are overloaded. This covers the period from scramble to the climb to Mach Y, $Y_1$ feet. Initial vectoring must be less accurate than is possible with the system. Errors are likely to occur in the broadcast of information. All parts of the three critical spans of time are heavily loaded. All means have been employed to distribute loads to bring the total at each moment below the 100 percent level.

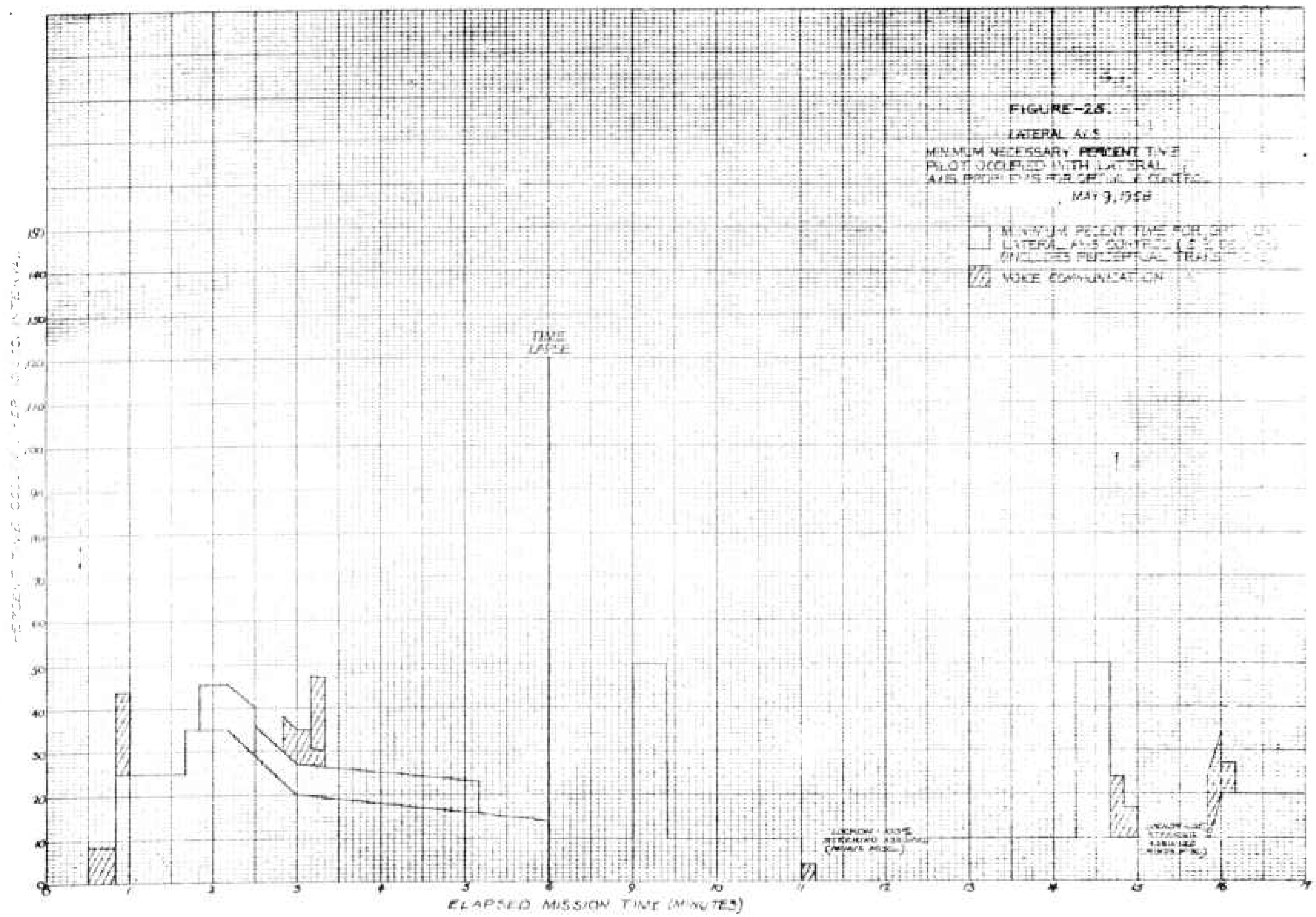


Figure 25. Lateral Axis — Minimum Necessary Percent Time Pilot Occupied with Lateral Axis Problems for Optimum Control

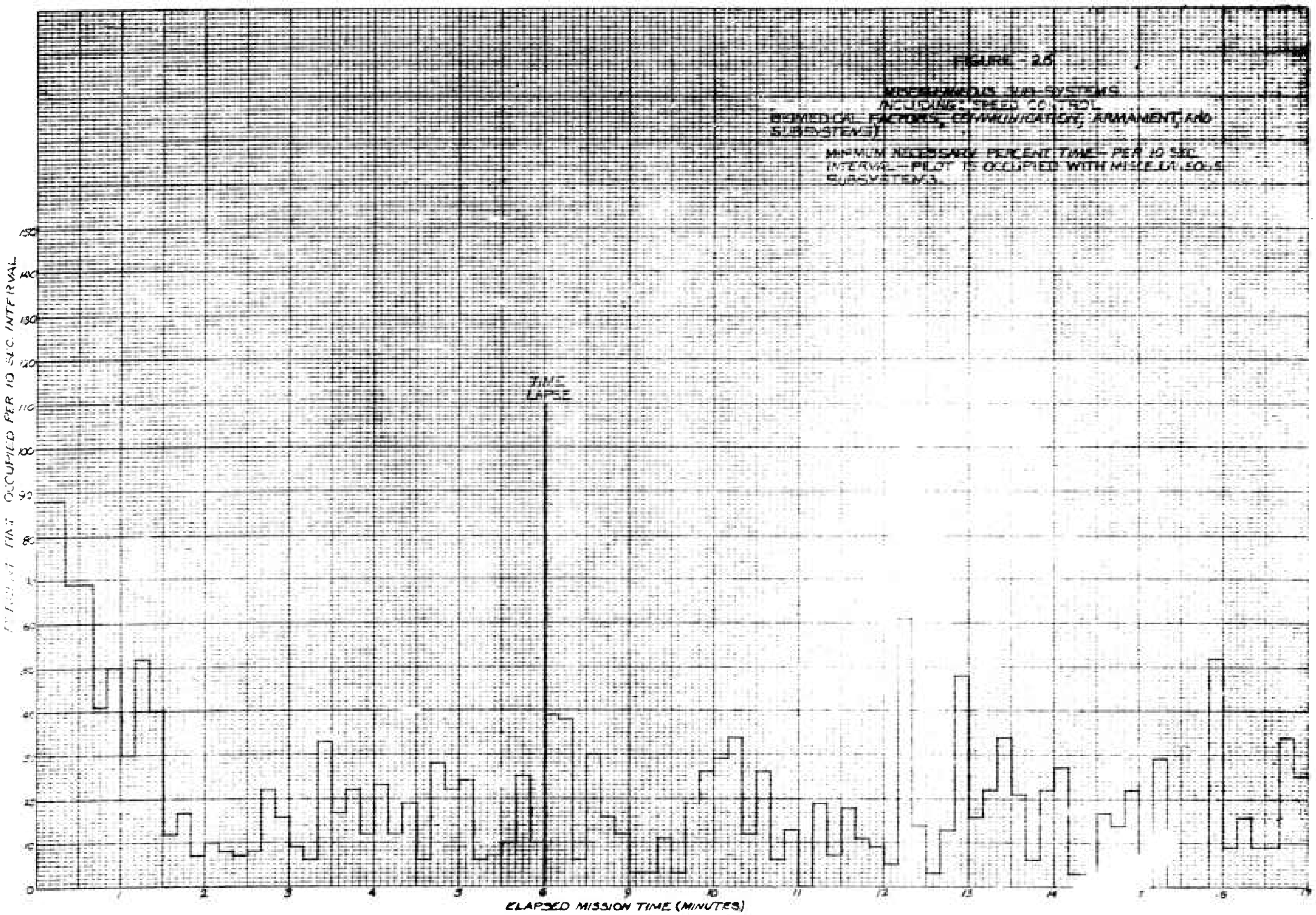


Figure 26. Miscellaneous Subsystems - Minimum Necessary Percent Time per Ten-second **Interval** - Pilot is Occupied with Miscellaneous Subsystems

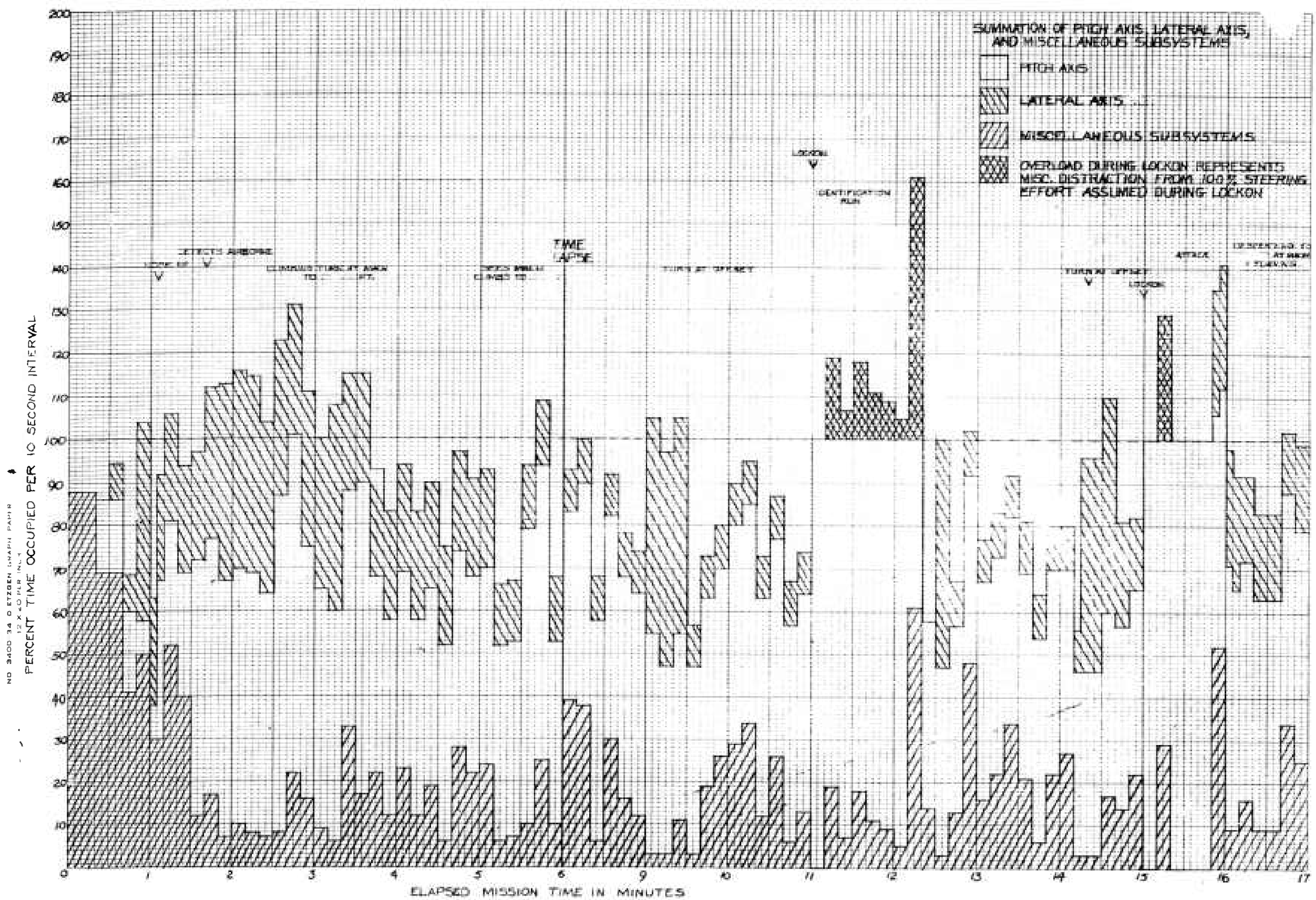


Figure 27. Summation of Pitch Axis, Lateral Axis and Miscellaneous Subsystems

It is concluded that the weapon system can be flown manually with difficulty, and that further instrument improvement is necessary to obtain the most from the equipment. The high vertical axis work load (60 to 80 percent during the overloaded period) appears to be the most promising area of system improvement. Estimates were made of possible system improvements with new instrumentation. The recommendation report which follows as Part II of this document will discuss these results.

## H. OTHER INTEGRATED INSTRUMENT SYSTEMS

Three advanced instrument systems were studied in relation to the weapon system:

Navy Contact Analog (ONR)
WADC Integrated Cockpit Display
Hughes Integrated Instrument System

The systems were studied by both Honeywell and by Dunlap and Associates on a subcontract basis. The Dunlap report is found in Appendix D of this report.

### Navy Contact Analog

The Navy Contact Analog system is not feasible for the aircraft for several reasons. The best information would indicate that hardware would not be available for installation for several years. In addition to this, the concept has not been shown to be superior for interceptor missions by any quantitative means. As attractive as the general idea is, the practical application to a combat aircraft would require an extensive program of considerable cost. The system also appears at the moment to be quite complex and of questionable reliability.

### WADC Integrated Cockpit System

The four major instruments of this system are:

1. Flight director-attitude indicator
2. Altitude-vertical speed indicator
3. Airspeed, Mach, safe speed indicator
4. Horizontal situation indicator

Two of the instruments are already a part of the Phase I system. The proposed IDI and flight director-attitude indicators are very similar to the WADC system suggestions. The speed and vertical situation indicators are the exceptions. Honeywell experiments have been run with these indicators and they have not been found equal in reading qualities to other instruments. Further, the tapes have always been found difficult to read when moving and are not recommended by WADC TR 54-160. Mengelkock and Houston of the University of Illinois have shown no advantage for the tapes in a series of experiments performed for WADC.* The instruments are designed contrary to WADC TR 54-160 in several respects.

1. The operator will not be able to see where the limiting Mach and stall limits are on the small airspeed and Mach scales.

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* Moving Tapes - Vertical Displays of Altitude Information, Mengelkock and Houston, WADC Reports 57-384, 57-549 and 57-385

2. The pilot must use compensatory rather than pursuit tracking of command indices.

3. Scale sensitivity.

Since there are several objections to the instruments from a reading point of view, the instruments are of questionable value. The original analysis of speed indication also showed the value of a pressure-driven indicated airspeed meter which is not possible with the WADC instrument.

In conclusion, it is felt that the desirable features of the WADC system are already incorporated in the Phase I system and that little would be gained from incorporating the speed and altitude instruments.

Hughes System

This system was found to be the most likely design of the three systems for an interceptor. The Phase I program incorporated several features of the Hughes concept. The principle of the moving part was carried out in the original Phase I recommendation. The Honeywell moving aircraft attitude indicator was an improved version of the Hughes flight director-attitude indicator.

Studies were conducted which showed the superiority of both the display and hardware configuration of the Phase I speed indication over the Hughes indicator.

The Hughes vertical situation indicator provides a good tactical planning scale. The display suffers, however, from having four pointers superimposed upon one another and thus making reading or identification difficult in many cases.

It was concluded that all three instrument systems were inappropriate for the aircraft although each had several points of merit. See Appendix D for a more complete comparison.

## I. SUPPORT STUDIES AND EVALUATION

In addition to the major analysis conducted by Honeywell, a number of the areas have been studied in more detail. Most of the studies have involved experimentation with human subjects after a program of study.

### Vertical Situation

Four vertical situation indication systems were evaluated for display characteristics. The four displays are shown in Figure 28.

| | |
|---|---|
| WADC | "A" |
| Hughes | "B" |
| Honeywell Experimental | "C" |
| Conventional (Phase I) | "D" |

The Honeywell experimental display system was designed to test for the possibility of display improvement in several areas. A new type of rate of climb indicator is used which presents quantitative and qualitative information. An arrow whose size and direction is supplemented by a counter for precise reading requirements is used. A counter is used for altitude information since it has been found superior in many experimental studies. A planning scale is provided. In order to check the feasibility of compressing the instrument, it was decided to shorten this scale, although this was shown to be inadvisable.

Seven college students and two experienced pilots were used as experimental subjects. The subject was seated in front of a simulated aircraft instrument panel that contained a lucite screen. A push button was given to the subject to project a slide onto the screen. The subject was told to take only as long a time as he felt necessary to get an accurate reading. Speed and accuracy was stressed throughout the experiment. The experimenter recorded both the viewing time and the subject's response. (See Table 4.)

The general instructions were read to each subject and a familiarization period and 15 practice slides preceded each instrument presentation.

There were 23 slides per instrument display. Each display was run through four times. The first time through on display No. 1, the subject read only altitude. The second time, rate of climb or vertical speed. The third time, command altitude, and the fourth time involved a problem-solving task. This procedure was repeated for each of the other three displays.

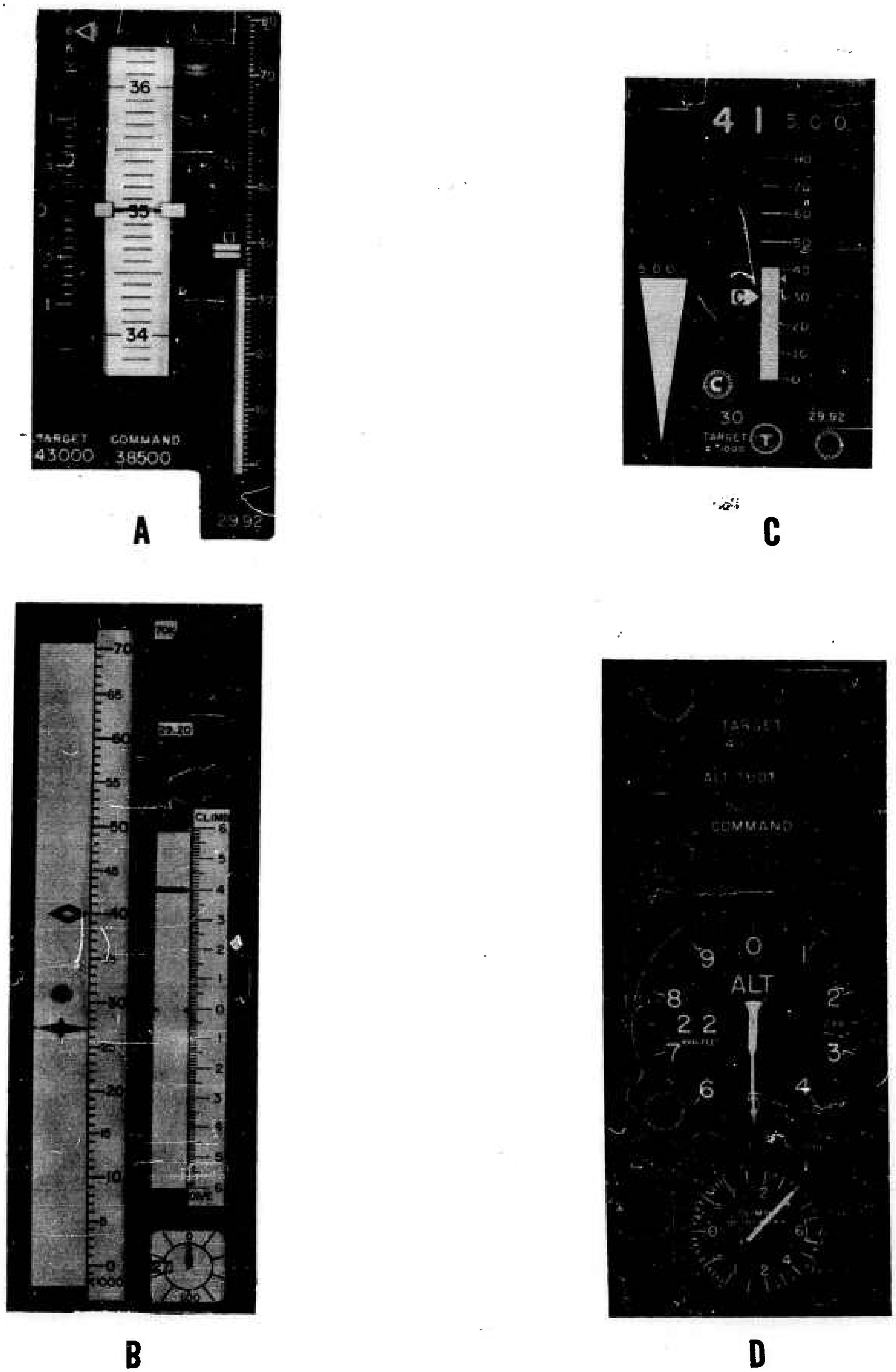


Figure 28. Vertical Situation Displays

Table 4. Reading Time and Error Frequency in Vertical Situation Displays

| | Display | | | |
|---|---|---|---|---|
| | A | B | C | D |
| **ALTITUDE** | | | | |
| Mean Reading Time (sec) | | | | |
| Novices | 0.75 | 1.03 | 0.31 | 0.52 |
| Pilots | 0.67 | 1.55 | 0.40 | 0.40 |
| Errors | | | | |
| Novices 0-500 feet | 8 | 62 | 0 | 3 |
| 501-1000 feet | 1 | 9 | 1 | 2 |
| greater than 1001 feet | 5 | 12 | 0 | 5 |
| Pilots 0-500 feet | 6 | 13 | 0 | 1 |
| 501-1000 feet | 1 | 2 | 0 | 4 |
| greater than 1001 feet | 0 | 3 | 0 | 4 |
| **VERTICAL SPEED** | | | | |
| Mean Reading Time (sec) | | | | |
| Novices | 0.72 | 0.72 | 0.40 | 0.60 |
| Pilots | 0.72 | 0.82 | 0.49 | 0.50 |
| Errors | | | | |
| Novices 0-500 ft/min | 8 | 11 | 1 | 12 |
| 501-1000 ft/min | 2 | 1 | 3 | 6 |
| greater than 1001 ft/min | 2 | 0 | 3 | 3 |
| Pilots 0-500 ft/min | 2 | 1 | 1 | 2 |
| 501-1000 ft/min | 1 | 2 | 0 | 0 |
| greater than 1001 ft/min | 0 | 0 | 0 | 0 |

Table 4. (Cont.)

| | Display A | B | C | D |
|---|---|---|---|---|
| **COMMAND** | | | | |
| Mean Reading Time (sec) | | | | |
| Novices | 1.16 | 0.95 | 0.84 | 0.42 |
| Pilots | 1.47 | 1.30 | 0.85 | 0.36 |
| Error | | | | |
| Novices 0-500 feet | 48 | 48 | 42 | 2 |
| 501-1000 feet | 38 | 6 | 56 | 0 |
| greater than 1001 feet | 33 | 11 | 16 | 9 |
| Pilots 0-500 feet | 13 | 11 | 10 | 0 |
| 501-1000 feet | 8 | 2 | 13 | 0 |
| greater than 1001 feet | 4 | 1 | 5 | 1 |
| **PROBLEM** (Pilots Only) | | | | |
| Mean Reading Time (sec) | 1.40 | 1.04 | 0.97 | 5.04 |
| Errors | 9 | 7 | 20 | 10 |

The problem-solving task involved more concentration and knowledge of aircraft maneuvers than did the other readings, so only the pilot's performance was evaluated. The pilot was required to give responses to the following questions for each slide:

1. What is my present condition? Am I climbing, diving or flying level?

2. What is my desired condition:

There were seven possible solutions to the problem; these were:

1. Maintain dive
2. Decrease rate of dive
3. Increase rate of dive
4. Maintain climb
5. Decrease rate of climb
6. Increase rate of climb
7. Maintain level flight

All four instruments had the same indicator settings which simulated the readings one would see during takeoff, climb to command altitude, tracking a target and descending. Vertical speeds were limited to 6,000 feet per minute in order to facilitate a direct comparison between the conventional and newer scales employed in this study.

## Attitude Indication

Several experiments were conducted in connection with the flight director-attitude indicator.

A Comparison of Moving Aircraft and Moving Horizon Indicators in Recovery from Unusual Attitudes under Conditions of Induced Vertigo:

The experiment was designed to test for possible interference effects of a moving drone indicator on a moving horizon display as a function of training with the moving drone during the stress of induced vertigo. Two experienced pilots were tested on their ability to recover from unusual attitudes under the influence of vertigo. A comparison between the Minneapolis-Honeywell FD-AI (moving drone display) and the Lear (moving horizon display) was made in terms of recovery performance. Time to recover and reversal errors in pitch and roll served as criteria

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for this study. The experiment continued for six days; performance on sixteen recovery tests for each instrument was recorded daily. Prior to each test item, vertigo was induced by turning the pilots in a rotary chair. Right and left rotations were given equally often and head orientation was systematically varied from upright, to the left and right shoulder, to head-down positions. An additional variable was the degree of experience with a moving drone display. Subsequent to the first experimental day, pilots received forty, two-minute trials a day tracking with the MH FD-AI in a simulated aircraft system; twenty trials preceding and twenty trials following the testing period. The results suggested that (a) exclusive training with a moving drone display did not impair recovery time or increase the number of reversal errors with the Lear indicator, (b) recovery time and reversal errors decreased for both instruments (no decrease in pitch errors, however, were observed with the Lear instrument), and (c) under conditions of induced vertigo, recovery with a moving drone was consistently superior to the moving horizon indicator. A total of 67 reversal errors, for example, were recorded for the moving horizon, whereas, only eight were observed with the moving drone display.

## Results

Figure 29 shows the percentage of reversal errors for both indicators in pitch and roll. It is noted that reversal errors were absent with the moving drone display after the second experimental session. Improvement in recovery performance is also observed with the moving horizon indicator for the roll dimension. Recovery in pitch, however, was not significantly different from the first to the last day. The total number of reversal errors for the outside-in display was eight, as compared to 67 for the inside-out presentation. (See Table 5.)

Recovery time data are given in Figure 30. Improvement is noted with both displays, but the overall superiority is in favor of the moving drone instrument. Improvement in recovery time is also a significant effect. (See Table 6.)

## Discussion and Conclusions

That training with the outside-in display for attitude indication did not interfere with performance on the inside-out display is clearly indicated by the results of this study. In addition, recovery performance with the moving drone display under the influence of vertigo was superior to the moving horizon indicator on the very first day of the experiment when neither pilot had previously experienced the former instrument. Improvement in recovery performance was observed with both indicators from the first to the sixth experimental session. From this result, it may be speculated that the

pitch and roll. It is noted that reversal errors were absent with the moving drone display after the second experimental session. Improvement in

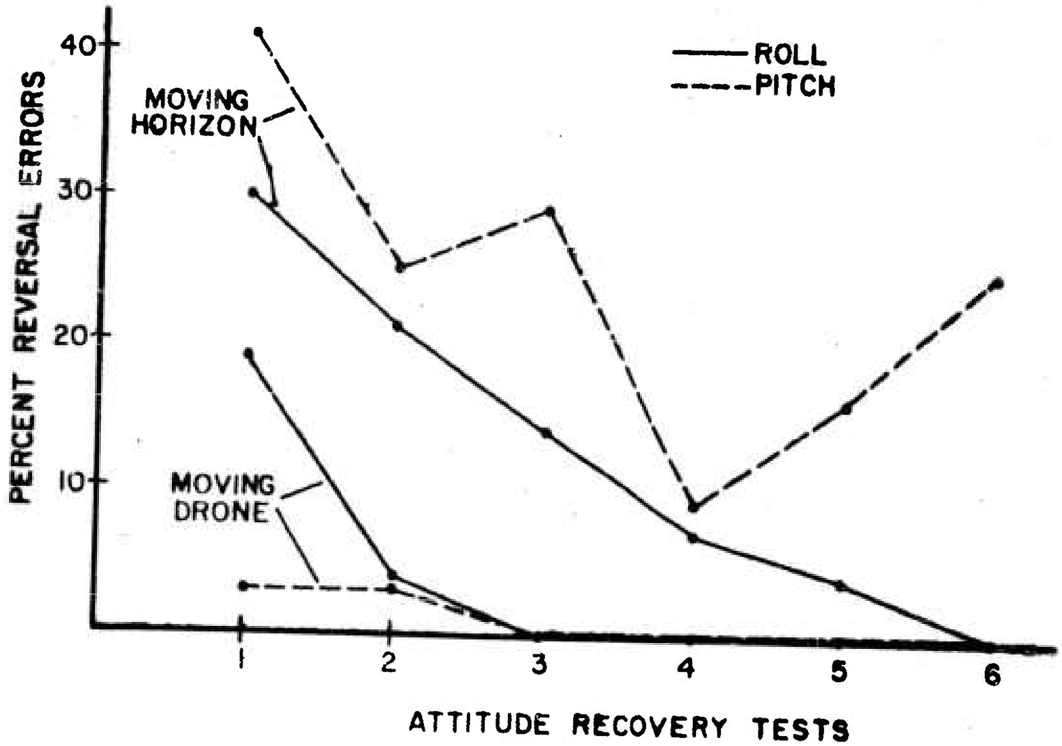



Figure 29. Percent Reversal Errors

recovery performance is also observed with the moving horizon indicator for the roll dimension. Recovery in pitch, however, was not significantly different from the first to the last day. The total number of reversal errors for the outside-in display was eight, as compared to 67 for the inside-out presentation (see Table 5.).

Table 5. Comparison of Reversal Errors during Recovery with the Moving Drone and Moving Horizon Attitude Indicators

| Sessions | | Horizon | Drone | Probability |
|---|---|---|---|---|
| 1-2 | Roll | 14 | 6 | 0.058 |
| | Pitch | 21 | 2 | 0.001 |
| 3-4 | Roll | 6 | 0 | 0.016 |
| | Pitch | 12 | 0 | 0.001 |
| 5-6 | Roll | 1 | 0 | -- |
| | Pitch | 13 | 0 | 0.001 |

Recovery time data are given in Figure 30. Improvement is noted with both displays, but the overall superiority is in favor of the moving drone

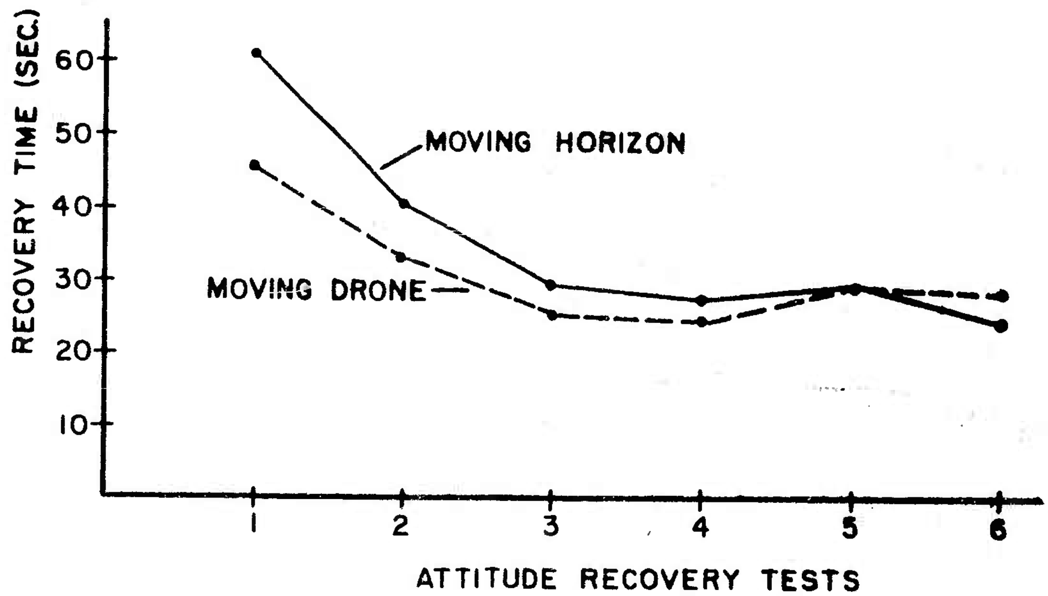



Figure 30. Average Time to Recover from Unusual Attitudes

estimated accident rate caused by pilot disorientation due to vertigo can be minimized if training procedures for pilots included recovery experience under induced vertigo; similar to procedures of this study.

It can be concluded that (a) the outside-in presentation leads to fewer misinterpretations of aircraft attitudes than the conventional display, and (b) negative transfer effects between instruments is either absent or negligible.

A Comparison of the MH Moving Drone FD/AI with Conventional Instruments in Various Steering Tasks:

Four pilots were given commands in roll, heading and beam displacement on both the MH moving aircraft flight director-attitude indicator and conventional instruments. Each pilot was evaluated by integrating the absolute error, difference between command and actual value, during the run. The smaller the error integral, the better the score.

Conclusions

The MH integrated instrument system was superior to the conventional instrument system. Little difficulty was experienced in transferring to the new instrument concept. Table 7 is a summary of the experiment.

Table 7. Comparison Mean of Integrated Error

| | Conventional | MH |
|---|---|---|
| Roll Angle Command | 200 | 116 |
| Heading Command | 118 | 59 |
| Beam Command | 284 | 231 |

Demonstration of the MH FD/AI Flying the Attack Phase of the Fire Control Simulation:

Three pilots flew the fire control problem as simulated by the analog computer. The simulation included tactical geometry, radar dynamics, noise and aircraft dynamics. The results compared favorably with current capability with the initial runs indicating about a 50 percent hit probability. A mechanical time-to-go indicator was also designed which could be incorporated into the instrument.

A Comparison of the MH FD/AI with the Hughes FD/AI:

The Minneapolis-Honeywell and Hughes FD/AI were compared for static presentations of navigation and approach problems. A variety of flight conditions were prepared for each instrument. Pilots and novices served as subjects for this experiment. They were required to make a single correction with a joystick for each of the slides. Novices were tested under two different stimulus exposure times (i.e., 1.0 second and 0.1 second), whereas, the pilots were presented all slides with an exposure time of 1.0 second. Time to respond and errors were recorded for each subject.

The difference between the Honeywell and Hughes FD/AI displays is not significant in terms of the criteria employed.

From the results of this study, it is reasonable to assume that differences between the Honeywell and Hughes instruments were not sufficiently exploited by the experimental method employed. With a continuous performance task (dynamic rather than static) practical differences between the two indicators may be revealed.

As a supplement to the experiment, subjects were requested to estimate the bank angle for each slide under two conditions of slide exposure time. In the first case they were instructed to make their estimates as accurately as possible, and were permitted to see the instrument as long as they wished. In the second case, subjects were limited to an exposure of 0.1 second. The results were as anticipated, viz, the Honeywell FD/AI proved to be superior for the estimation of bank angle. The mean error in degrees of bank angle for the longer exposure time was 3.0 degrees and 6.9 degrees with the Honeywell and Hughes indicators, respectively. The error in bank angle was increased to 6.1 degrees and 8.5 degrees with the 0.1 second exposure.

Flight Path Angle Presentation for a FD/AI:

It has been suggested by pilots and experimental evidence that some means of indicating flight path angle instead of pitch attitude be displayed on a moving airplane-fixed horizon type attitude indicator for aircraft flying at high speeds. This is based upon the consideration that control of the aircraft's flight path is more basic than maintaining pitch attitude. The wide range of angles of attack encountered in high speed aircraft, especially with delta wing configurations, would make the conventional pitch attitude display more difficult to use.

Since the flight path angle is approximately equal to the difference between pitch attitude and angle of attack in the no-roll condition, we can use these two quantities to obtain flight path angle. At high altitudes and/or low Mach number the flight path change of the aircraft may initially lag a pitch attitude change by several seconds. The amount of this lag is a function of aircraft dynamics, damper

configuration, Mach number and altitude. Since this lag may be appreciable, flight path angle may not be what the pilot wants indicated to him.

A presentation was developed which presented flight path angle in the steady-state condition while also having the transient pitch attitude change. In order to do this, it is proposed to eliminate the initial delay of $\gamma$ presentation by lagging the angle of attack input and then indicating this new difference ($\gamma'$) between pitch attitude and lagged $\alpha$ ($\alpha'$). By this means a better display may be obtained.

An analog computer analysis was conducted to determine an optimum display. A flight path angle presentation with a lagged angle of attack input was found which could be used in all modes of operation.

This display was then evaluated with four pilots under three flight conditions with several types of problems. Pilot control was not improved by changing the dynamics of the flight path angle presentation. The pitch axis damper appears to solve the problem we expected the pilots to encounter.

## Engine Instruments

Comparison of Four Integrated Instrument Systems:

Four designs of an integrated engine instrument were evaluated by the method of static display presentations. (See Figure 31.) All instruments presented quantitative information on the percentage of available thrust and qualitative information of exhaust gas temperature. Slides were constructed depicting two engine instruments and a Mach meter. The controls simulated two throttles. Two series of 40 engine performance problems were developed; one series representing, in part, realistic flight conditions and a second random group. Significant differences in instrument performance were observed with the sequential set of problems, where no differences were observed with the random series.

The linear engine display showed some superiority over the round dials in cases where matching of thrust was necessary. The warning plaque on the linear instrument proved to be too small and was hard to read. The round instruments with a central warning plaque proved superior for check reading.

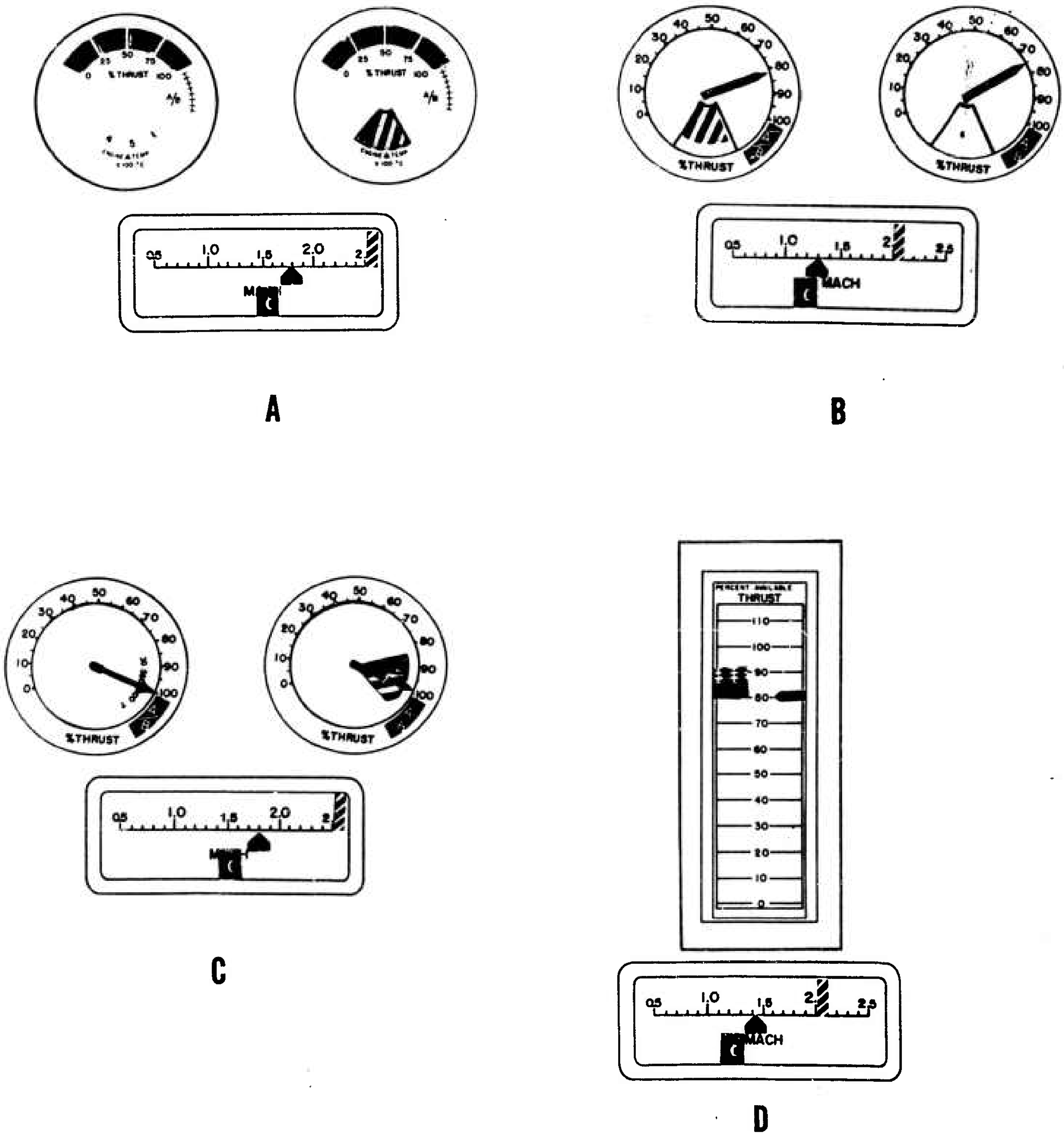



Figure 31. Four Designs of an Integrated Engine Instrument

## Application of Sampled-Data Techniques to Determine Pilot Work Load in a Continuous Task

An initial look was taken into the possibility of analytically determining pilot work load by application of sampled data techniques to a single-loop control system which includes the human operator as a component. In order to interpret such a system as a sampled data system with constant sampling rate, it was assumed that the human operator can be represented by a transfer function consisting of a constant-rate sampler, a "zero-order" hold, a transportation lag (pilot reaction time) and a lead component.

This analysis was stopped after it became apparent that the computations involved were becoming prohibitive. The analysis was carried out to one result which was checked by having several subjects control the investigated function on the analog computer in a time sampling technique. Some correspondence was evident which tended to disappear as the operator became experienced and was subjected to low sampling rates.

COMBAT OPERATIONAL ANALYSIS

MACH = ALT. =

Sheet 1 of 7

ASSUMPTIONS 1. Armament: Missiles 2. Environ. (worst possible) 3500' alt, 100°F 3. Initial wgt: including: max internal fuel: Missiles: Heaviest take off wgt
4. Slowest times for: start, idle, full thrust, take off (15, 25, 7, and 28 secs respectively) 5. Manual steering 6. Broadcast Manual Control
7. The necessary items have been checked during the "available" and "readiness" conditions (this analysis begins with A/C in "standby" condition)

| OPERATIONAL PHASE | LAPSD. MISS. TIME (SEC) | INFORMATION NEEDED BY PILOT TO MEET IMMEDIATE MISSION REQUIREMENT | CONTROLS | INSTRUMENTS | READINGS PRESENT | READINGS DESIRED | PILOT ACTION | TIME PILOT CH. | TIME MISS. | PERCEPTUAL INPUTS TO PILOT K = Kinaes V = Visual A = Audit T = Tactl | MOTOR OUTPUTS S = Speech RH = Rgt Hd LH = Lft Hd F = Feet | FUEL RMDR LBS = AMT USED | DIST FLOWN (N.M.) | A/C WGT (LBS) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| STAND BY PRE-FLIGHT & TAKE OFF | 0 | Pre 1. Scramble signal / Wheels secure? / Area clear? | throttles | EPI (EGT) RPM | 0 rpm | 2000 rpm | 1. Throttles to "start" | 28 | 1 | A, V out / V in | LH | | | |
| | | | Eng. switch | | 0° | max | 2. Master Electric Switch | | 1 | V in | RH | | | |
| | | | Ignition Switch | Fuel flow | 0% | % | 3. Engine switches on | | 1 | V in | RH | | | |
| | | | Master Elec Sw throttle | EPI thrust | 0 lbs 0% | lbs % | 4. Advance throttle to "idle" as EGT reaches X° | | 3 | V in | LH | | | |
| | 28 | 1. What are temp limits for acceptable start? 2. Hanger doors open? | Canopy Lever | | | | 5. Close canopy | 20 | 4 | V in V out | LH | | | |
| | | | Cabin Press Switch | | | | 6. Pressurize Cabin | | 1 | V in | RH | | | |
| | | | | | | | 6.1 Switches to normal fuel from emergency | | | | | | | |
| | 48 | 7. Intercept ("command") heading and alt. | Press to talk Switch | EPI | | | 7. Revs & acknowledges intercept heading & alt. from ground control | 20 | | A | LH, S | | | |
| | | | Parking brake | | | | 8. Releases parking brake | | | V in V out | T | | | |
| | 51 | 9. What setting to get optimum taxi speed (= fastest possible taxi 75 kts max for turn) | throttles | EPI | | ? | 9. Adjusts throttle for taxi | 3 | | V in V out | LH | | | |
| | 64 | 10. Where is A/C with respect to runway? Center, off to left, etc. | Nosewheel str. button rudder pedals | | | | 10. Steers A/C toward runway | 20 | | V out | F | | | |
| | 66 | 11. What is ground speed? | Throttles | (TAS?) | | | 11. Throttles back and brakes for turn to runway | | 2 | V out | LH, F | | | |
| | 68 | | Throttles | EPI | ? | 100% | 12. Advance throttles to full power for immediate take-off | | 7 | V in | LH, F | | | |
| | | 13. Where is axis of A/C with respect to ℄ of runway? | | | | | 13. Lines up with runway | | 4 | V out | T | | | |
| | 71 | | Nosewheel lock | | | | 14. Locks nosewheel | | 1 | V out | RH | | | |
| | | 15. Am I keeping A/C down center of runway? | Brakes rudder | | | | 15. Steers down runway | 15 | | V out | F | | | |
| | | 16. Are engines performing correctly? | Brakes rudder | EPI thrust IAS EGT | Taxi 75 Safe | 100% safe A/B speed | 16. Observes instruments, runway | | 1 | V in V out | F | | | |
| | | 17. Has IAS reached A/B ignite pt. | Brakes rudder A/B ignite | IAS | 75 | | 17. Observes reaching A/B speed | | [illegible] | V in | F | | | |
| | | | | | | | 18. Lights A/B | | [illegible] | V in | LH, F | | | |
| | | 19. Is A/C still properly centered on runway? | Rudder | | | | 19. Glances at runway | | [illegible] | V out | F | | | |
| | | 20. Has A/B ignited? Is temp in safe zone? Has IAS reached "takeoff-attitude" speed | Rudder | EPI thrust EGT IAS | 100% safe | 100% + A/B safe | 20. Check instruments | | 2 | V in | F | | | |
| | 86 | | Stick | IAS | | | 21. Sets "takeoff" attitude | | | V | RH | | | |
| | | 22. A/C is airborne | Stick | IAS EPI | T.O | T.O + | 22. Detects that he is airborne | 13 | 1 | V | RH | | | |
| | | 23. Is landing gear retracting? | Landing gear Lever stick | | | | 23. Retracts landing gear | | 2 | V in | LH, RH | | | |
| | 99 | 24. Is landing gear up and locked | Stick | Landing gear Ind | Down | up & locked | 24. Observes lndg gear indicators | | 2 | V in | RH | | | |
| FLIGHT TO OFFSET | | 25. Is A/C trimmed? | Trim button (stick) | A.I | T.O. att. | St. & lev | 25. Adjust trim flys level while accelerating | 33 | 4 | V in | RH | | | |
| | | 26. Am I accelerating? | Stick | IAS Mach EPI | | | 26. Continues accelerating to | | | V in V out | RH | | | |
| | | 27. Which direction do I turn to new heading? | Stick | FND | | | 27. Learns from NAV. that he can use FNDs | | 4 | A, V in | RH | | | |
| | | 28. What is opt. bank angle for X° change of heading? | Stick | FND AI | T.O. Hdng | intercept heading | 28. Turns toward heading | | Vari-able | V in V out | RH, F | | | |
| | | 29. Has mach reached | Stick | Mach | | | 29. Observes mach at | | 2 | V in | RH | | | |
| | | 30. Am I breathing oxygen? | Stick | | | | 30. Checks oxygen flow | | 1 | V in | RH | | | |
| | | | Stick | Mach EGT Alt | safe | safe | 31. Climbs to | 53 | | V in V out | RH | | | |
| | | 32. Are engines ok? Sub systems ok? Am I holding Mach? Holding heading? | Stick | FND IDI Mach EPI Alt Att R/C Status Panel (os, hydr, elec, etc.) | sn[illegible] ang status; Varies to hold mach; Varing to hold mach; No info = OK | | 32. General instrument check (primary flt) status panel (secondary systems) | | 15 | V in | RH, LH | | | |

COMBAT OPERATIONAL ANALYSIS MACH ALT. (Continued)



| OPERATIONAL PHASE | LAPSD. MISS. TIME (SEC). | INFORMATION NEEDED BY PILOT TO MEET IMMEDIATE MISSION REQUIREMENT | CONTROLS | INSTRUMENTS | READINGS PRESENT | READINGS DESIRED | PILOT ACTION | TIME PILOT OP. | TIME PILOT MISS. | PERCEPTUAL INPUTS TO PILOT K = Kinaes V = Visual A = Audit T = Tactl | MOTOR OUTPUTS S = Speech RH = Rgt Hd LH = Lft Hd F = Feet | FUEL RMDR LBS =AMT USED | DIST FLOWN (N.M.) | A/C WGT (LBS) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| FLIGHT TO OFFSET (Continued) | | 33. When do I begin leveling off | Stick | PND ALT IDI | Hold | | 33. Levels off for | 53 | | V in | RH | | | |
| | 185 | 34. Which way to turn to correct heading? | Press-to-talk button Stick | IDI | Orig. Hdg. | Revised Heading | 34. Receives & acknowledges revised course & alt. data from ground control | | 10 | V in | LH RH | | | |
| | | 35. When do I recenter stick to arrive on heading? | Stick | PND IDI | Command Original revised | | 35. Corrects heading | 133 | X | V in | RH | | | |
| | | | Stick | Scane primary flt & status inst monitors mach | | | 36. Accelerates to mach | | | V in | RH | | | |
| | 318 | 37. Full $O_2$ flow? Cabin press. ok? Cabin temp. ok? | Stick | Oxygen PND | 100% follow | 100% command | 37. Checks oxygen, cabin press. alt. cabin temp. | | 6 | V in | RH | | | |
| | 319 | 38. Am I at m? | Stick | mach | | | 38. Observe mach = | 1 | | V in | RH | | | |
| | 472 | 39. When do I begin to level out for ? Am I maintaining mach No.? | Stick Trim Button Stick | PND mach PND Alt Mach | follow | command | 39. Climbs to | 153 | | V in | Rh | | | |
| | | | | | | | 40. Levels off at | | | V in | RH | | | |
| | | 41. What throttle setting to maintain mach = ? | Throttles | Mach | | | 41. Adjust throttles | | | V in | RH | | | |
| | | 42. Is status being maintained? | Stick Stick Throttle | PND IDI Alt Att Mach EPl Oxy. Status Panel | Hold Hold at Scan Hold M= Normal Hold Operating Scene | | 42. Cruises at | 78 | | V in V out | RH | | | |
| | | 43. Which direction to turn to correct course? | Stick | IDI PND Alt Mach | Old Hdng New Follow Command Hold Hold | | 43. Corrects course based on new ground information | | 20 | V in | RH | | | |
| | 550 | 44. When do I reach off-set point? | Press to talk button | IDI PND Mach Alt Fuel | | | 44. Receives & acknowledges data on position of offset pt. & direction of turn at offset | 32 | | A,V in | S RH | | | |
| | | | Stick | PND | Cruise Hdng | Offset Hdng | 45. (Reaches offset) Observes PND indicates turn | | 1 | V in | RH | | | |
| | 582 | 46. When do I stop turn? | Stick | PND Att Mach | Change to new hdng Hold level Hold M | | 46. Turns A/C to follow PND | | 2 | V in | RH | | | |
| | 617 | | Stick | PND Alt Mach Engine Status | Hold | | 47. Completes turn & flys PND at. and level | 39 | | V in | RH | | | |
| ACQUISITION AND IDENTIFICATION | | 48. What is result of "IFF" | Stick | PND Att Mach | | | 48. Receives information from Nav. that target has been detected | 4 | | A,V in | RH | | | |
| | 621 | | Stick | | | | 49. Receives information that IFF is negative, from Nav. | 2 | | A,V in | RH | | | |
| | 623 | 50. Is bogey friend or foe? | Stick | Monitoring: PND IDI Mach Alt | Follow Command Hold heading .0 Hold K' Hold | | 50. Decides on identification pass and informs Nav. Flys at. and level | 46 | 3 | V in | S RH | | | |
| | 669 | 51. Is Radar malfunctioning? | Stick | Radar | Erratic | | 51. Observes Radar erratic and checks with Nav. | 6 | | V in A | S RH | | | |
| | 675 | 52. When will Radar stabilize? | Stick | Check PND R/C Att Alt Mach | St. & L Hold Hold Hold | | 52. Flys instruments at. & level | 5 | | V in | RH | | | |

COMBAT OPERATIONAL ANALYSIS MACH = ALT. = (Continued)



| OPERATIONAL PHASE | LAPSD. MISS. TIME (SEC) | INFORMATION NEEDED BY PILOT TO MEET IMMEDIATE MISSION REQUIREMENT | CONTROLS | INSTRUMENTS | READINGS PRESENT | READINGS DESIRED | PILOT ACTION | TIME PILOT OP. | TIME PILOT MISS. | PERCEPTUAL INPUTS TO PILOT K = Kineas V = Visual A = Audit T = Tactl | MOTOR OUTPUTS S = Speech RH = Rgt Hd LH = Lft Hd F = Feet | FUEL RMDR LBS = AMT USED | DIST FLOWN (N.M.) | A/C WGT (LBS) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ACQUISITION AND IDENTIFICATION (Continued) | 680 | | Stick | Radar | | | 53. Radar stabilizes pilot observes | 1 | | V in | RH | | | |
| | 681 | | Stick | PND | Command New Heading | | 54. Corrects course by radar command | 5 | | V in | RH | | | |
| | 686 689 | 55. What is approx flying time for miles? Which side of interceptor will target be on? How big is target at miles? | Stick | IDI | | | 55. Receives information that range to target is miles | 3 | | V out, V in | RH | | | |
| | 695 | 56. Where is bogey? | Stick | | | | 56. Looks out to search for target | 6 | | V out | RH | | | |
| | 697 | | Stick | | | | 57. Receives information that range to target is miles | 2 | | A, V out | RH | | | |
| | 698 | | Stick | | | | 58. Detects target | ↓ | | V out | RH | | | |
| | 701 | | Stick | | | | 59. Informs Nav | 3 | | V out | S RH | | | |
| | | 60. When do I turn toward target? How much retard throttles? | Stick | PND | Follow Command | | 60. Flys st. and level | 25 | | V in, V out | RH | | | |
| | 726 | 61. What is targets identification number? | Throttles Stick | | | | 61. Retards throttles starts turn to pursue target. (reaches course parallel to target.) | ↓ | | V in, V out | LH RH | | | |
| | | | Press to talk button Stick | | | | 62. Flies past target & reads ID number to ground control | 10 | | V out | S, LH, RH. | | | |
| | | 63. Which way to break from target | Throttles Stick | | | | 63. Advances throttles and breaks from target to fly course to attack offset | ↓ | | V in, V out V in | LH RH | | | |
| | 736 | 64. Which direction to correct course? | Stick | PND Mach Alt | | Correct Hold Hold | 64. Receives information from Nav. to fly PND | 120 | | A, V in | RH | | | |
| | | | Stick | PND | Follow Command | | 65. Corrects course | | 6 | V in | RH | | | |
| | | 66. Am I holding correct course? | Stick Throttle | Scans { PND EPI Fuel Mach Alt | Hold Check status Hold @ M= Hold | | 66. Flies st. & level following PND Adjusts throttles at M= | | | V in | RH LH | | | |
| | | 67. Is target hostile? | Stick | PND | Hold | | 67. Receives info on range & range-rate from Nav. | | 3 | A, V in | RH | | | |
| | | | Press to talk button Stick | | | | 68. Receives & acknowledges info from ground control that target is hostile | | 10 | A, V in | S LH RH | | | |
| | 856 | 69. What is the best missile selection to make? | Armt. select switch Arm. Switch Stick | "Armt available" indicator | Available | Available | 69. Selects & arms missiles | ↓ | 11 | V in | RH LH | | | |
| ATTACK AND ASSESSMENT | | 70. Am I holding course? How long before offset? Which direction to turn at offset? | Stick | Scan EPI Status PND Mach Alt | Follow Command Hold Hold | | 70. Continues to fly PND | 40 | | V in | RH | | | |
| | | | Stick | PND | Old | New | 71. Sees PND command turn at offset | | 1 | V in | RH | | | |
| | | 72. How steep a bank to get to new heading? | Stick | PND | Follow Command | | 72. Moves stick to turn A/C | | 2 | V in | RH | | | |
| | | 73. When do I get to new heading? | Stick | PND | Command | | 73. Sees PND command st. & level flight | | 1 | V in | HH | | | |
| | | | Stick | PND | Old - New Heading | | 74. Adjusts A/C to st. & level | | 2 | V in | RH | | | |
| | | 75. How far to target? | Stick | PND | | | 75. Receives info on target detection ECM & breakaway heading from Nav. | | 6 | V in | RH | | | |
| | | | Stick | | | | 76. Holds course | | | V in | RH | | | |
| | | | Stick | PND | Follow | | 77. Receives info that IFF response is again missing | | 2 | A, V in | RR | | | |
| | | | Stick | PND | Follow | | 78. Informs Nav. to continue attack | | 2 | S RH | | | | |
| | | | Radar | Erratic | | | 79. Notes radar become erratic check with Nav. | ↓ | 2 | V in A | S | | | |
| | 896 | 80. When does Radar stabilize? | Stick | AI IDI | Hold Hold | | 80. Flies clocks | 34 | 5 | V in | RH | | | |
| | | | Stick | Radar | Steering Dot | | 81. Nav. informs pilot to use radar | | 2 | V in | RH | | | |
| | | | Stick | Radar | Steering Dot | | 82. Flies radar and watches time to go | ↓ | 5 | V in | RH | | | |

COMBAT OPERATIONAL ANALYSIS MACH = .3 ALT. = (Continued)



| OPERATIONAL PHASE | LAPSED MISS. TIME (SEC) | INFORMATION NEEDED BY PILOT TO MEET IMMEDIATE MISSION REQUIREMENT | CONTROLS | INSTRUMENTS | READINGS PRESENT | READINGS DESIRED | PILOT ACTION | TIME PILOT OP. | TIME PILOT MISS. | PERCEPTUAL INPUTS TO PILOT K = Kinest V = Visual A = Audit T = Tactl | MOTOR OUTPUTS S = Speech RH = Rgt Hd LH = Lft Hd F = Feet | FUEL RMDR LBS = AMT USED | DIST FLOWN (N.M.) | A/C WGT (LBS) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ATTACK AND ASSESSMENT (Continued) | (896) | 83. Pilot needs basis for deciding on decoy | Stick | Radar | Steering Dot | | 83. *Possible choice: attack or ignore homing decoy? | (34) | 2 | A, V in | RH S | | | |
| | | 84. Are the desired missiles armed and available? | Stick | "Armt available" indicator Armt select | Available | | 84. Checks arming of missiles | | 4 | V in | RH | | | |
| | 930 | 85. 20 seconds to go | Stick | Radar | Steer within circle | | 85. Notes TTG passes T max | 20 | 1 | V in | RH | | | |
| | | | Stick | Radar | | | 86. (See 83) | | | | | | | |
| | | | Stick | Radar | | | 87. *Possible choice: optical ranging or not. | | | | | | | |
| | | | Stick | Hold within circle | | | 88. Makes final correction to center FND | | | V in | RH | | | |
| | | 89. When do I break away? | Stick | Radar | Within circle | | 89. Fires armament | | | V in | RH | | | |
| | 950 | 90. Hit or miss? | Stick | | | | 90. Moves stick for breakaway and looks out for missile trail toward target. | | 3 | V out | RH | | | |
| | 953 | 91. Is target destroyed? | Stick | | | | 91. Continue turn & dive: sees missile explode at target sec after firing | | 2 | V out | RH | | | |
| | 955 | | Press to talk switch | | | | 92. Calls ground control & reports strike | | 3 | V in | S LH RH | | | |
| | 958<br>959 | 93. Time to retract launcher, & disarm | Stick Launcher retract "Arm" off | | | | 93. Retracts launcher flips "Arm" switch off. | | 1 | V in | RH | | | |
| RETURN TO BASE | 963 | 94. Am I turning in right direction? | Stick | IDI | | | 94. Receives heading to base from Nav. | | 4 | A, V in | RH | | | |
| | | | Stick | IDI Att | | | 95. Continues turn to base via IDI | | 8 | V in | | | | |
| | 971 | 96. What is correct throttle setting? | Throttle Stick | EPI Mach | Monitors descent Full A/B | | 96. Reduce power to setting for cruise | | 2 | V in | LH RH | | | |
| | 973 | 97. When is turn completed? | Stick | FND | | | 97. Receives info to fly FND from Nav. | | 3 | A, V in | RH | | | |
| | 976 | | Stick | FND | Follow Command | | 98. Corrects heading to fly FND | | 5 | | | | | |
| | 981 | | Stick | FND | On Command | | 99. (Turn completed) Notes that FND indicates turn completed | 10 | 1 | V in | RH | | | |
| | 991<br>992 | 100. Am I flying st. on heading? When do I reach cruise alt? | Stick | FND Alt | On Command | | 100. Corrects heading with stick to hold FND Command | | 2 | V in | RH | | | |
| | 994<br>995 | | Stick | Att | Level | Level | 101. Completes descent | | 1 | V in | RH | | | |
| | 997 | 102. Am I holding alt? | Stick | Alt FND Att | Level | | 102. Corrects att. with stick to fly st. & level. Follows FND | | 2 | V in | RH | | | |
| | | 103. Am I maintaining stable cruise, no malfunctions, enough fuel for return? | | | | | 103. Cruises back to base at ft M = | 1571 | | | | | | |
| | | | Throttle Stick | Primary Flight Status EPI Fuel IDI | Maintain stable cruise No trouble No trouble Sufficient for cruise | | 104. General instrument check | | 120 | V in | RH | | | |
| | | 105. Do I fly in directly or stack? | Press to talk button Stick | | | | 105. Requests approach clearance Reports position & armament | | 6 | V in A | S LH RH | | | |
| | | 106. What is correct alt. setting? | Press to talk button Stick | | | | 106. Receives & acknowledges info on holding pattern on radio fix near base & expected approach time | | 15 | A | S LH RH | | | |
| | 2568 | | Alt. set | Alt | | | 107. Corrects altimeter | | 3 | V in | RH LH | | | |
| | | | | | | | 108. Checks approach plate (length & width of runway, Min. alt. around field, freq. of radio bands available, etc.) | | 10 | V in | RH | | | |

COMBAT OPERATIONAL ANALYSIS

MACH = ALT. = ' (Continued)



| OPERATIONAL PHASE | LAPSD. MISS. TIME (SEC) | INFORMATION NEEDED BY PILOT TO MEET IMMEDIATE MISSION REQUIREMENT | CONTROLS | INSTRUMENTS | READINGS PRESENT | READINGS DESIRED | PILOT ACTION | TIME PILOT OP. | TIME PILOT MISS. | PERCEPTUAL INPUTS TO PILOT K=Kiness V=Visual A=Audit T=Tactl | MOTOR OUTPUTS S = Speech RH = Rgt Hd LH = Lft Hd F = Feet | FUEL RMDR LBS = AMT USED | DIST FLOWN (N.M.) | A/C WGT (LBS) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| RETURN TO BASE (Continued) | (2568) | 109. Rate of descent, heading, at approach (read from ground) timing for pattern turns | Stick Throttles (Adjust) | Alt Mach R/C IDI Clock | Level Pattern hold | Max endur Des 500/min | 109. Descends to & establishes holding pattern | 900 | 300 | V in, V out | RH LH | | | |
| | 3468 | 110. Pressurization, finding gear max IAS speed brakes (if needed) armament safe, brake parachute | Stick | R/C Status P. Mach IDI Alt Clock | Level Blank | Level Landing check list | 110. Runs through landing check off wheels down, brake chute, etc. | | 10 | V in | RH LH | | | |
| | | | Arm. safe switch | | Safe | Safe | 111. Checks armament | | 2 | V in | RH | | | |
| | | 112. When do I level out for approach? | Stick Throttle (Adjust) | R/C Alt FDAI IAS | Level Follow needle | Des 5000/M | 112. Descends to reduces speed | 178 | | V in, V out | RH LH | | | |
| | | 113. What is tower freq? Am I getting tower on UHF? | UHF Freq. select | UHF readout | | | 113. Switches UHF to tower frequency | | 2 | V in | LH | | | |
| | | 114. Are FDAI needles showing AQCA? | FDAI mode select | | Nav. | App. | 114. Switches FDAI to approach mode (AQCA) | | 2 | V in | LH | | | |
| | | 115. What is approach speed for present weight? | Speed brake switch | IAS | | App Spd | 115. Extends speed brakes - observes S.B. out | | 2 | T | LH | | | |
| | | 116. Lnd. gear down & locked? | Lnd gear lever | | | | 116. Observes speed, extends landing gear | | 15 | V in | LH | | | |
| | | | Stick | Lnd gear ind | Down & Cmd | | 117. Observes lnd gear down & locked | | 2 | V in | RH | | | |
| | | 118. Is A/C trimmed? | Trim button Stick | Fd att. ind | | | 118. Trims A/C for new configuration | | | T, V out, V in | RH | | | |
| | | 119. Am I on needle - commanded glide slope? | Stick | FDAI | Follow needle command | | 119. Flys needles on FDAI | | | V in | RH | | | |
| | | 120. Location of touchdown spot | Press to talk | | | | 120. Reports visual contact with the runway, rcvs lnding clear | | 3 | A, V out | LH S | | | |
| | | 121. Am I at correct appoach speed? | Throttles | IAS | Follow command | | 121. Adjusts throttles | | 2 | V in | LH | | | |
| | | 122. Maintaining touch down point | Stick | | | | 122. Closely watches touch down point on runway, and | | | V out | | | | |
| | | 123. Am I too close to stall speed? | Throttles Stick | | | | 123. Adjust throttle to hold touch-down point | | 3 | V out | LH RH | | | |
| | | 124. Am I at correct T.D. attitude | Throttles Stick | | | | 124. Retards throttle & establishes touchdown attitude | | 3 | V out | RH | | | |
| | | | Stick Rudder pedal | | | | 125. Touches down | | | T, V out | RH F | | | |
| | | 126. Will I be able to stop in time? | Brake chute Control lever | | | | 126. Release parachute brake | | 2 | V in, T | | | | |
| | | 127. Which taxi strip do I use? | Rudder Brakes | | | | 127. Uses rudders & brakes to maintain straight path, and | | | V out | F | | | |
| | | 128. Is my ground speed low enough to turn into taxiway? | Brakes | | | | 128. Slows A/C | | 30 | V out | F | | | |
| | 3846 | 129. Am I clearing other A/C in the area? | Brake | | | | 129. Makes turn at nearest taxiway | | | V out | F | | | |
| TURN AROUND | | | Throttles Brakes | | | | 130. Taxis A/C to loading site and stops | 300 | 30 | V out | LH F | | | |
| | | | | | | | 131. Extends launchers beneath A/C onto dolly | | 15 | V in | | | | |
| | | 132. Is A/C properly re-armed? | | | | | 132. Makes confidence check of armament system | | 25 | V in | | | | |
| | | 133. Are launchers retracted? | Launcher retract button | | | | 133. Retract launchers into A/C | | 15 | V in | RH | | | |
| | 4146 | | Throttles Parking brakes Foot brakes | | | | 134. Taxi A/C to duty runway | | 30 | V out | LH F | | | |

COMBAT OPERATIONAL ANALYSIS PHASE II MISSION MACH = Z, ALTITUDE = $Z_1$

Discussion

4. May take 25 sec. to get up to idle. (See p. 24 "Aircraft Readiness Facility".)
5. Canopy closing takes 4 sec. He holds switch until closed. Latches manually.
8. Also observes hanger doors open full.
11. Both optional. He cannot exceed 74 kts in runway turn.
13. He is moving at 75+ kts "Lines Up" refers to one or two corrections.
15. Brakes and rudders used simultaneously for smooth transition.
16.
17. Visual system heavily loaded from (8) to (22).
18.
19. To correct steering this probably is done several times between (15) and (19).
21. Can pilot do this by observing attitude Ind? Or is it "seat of pants"?
25. Intermittent trim adjustments will continue throughout changing modes.
27. *Primary Nav. display
31. During climb he adjusts att. to hold mach. R/C varies from X 1/min @ X, altitude to y'/min @ y. altitude. Standard rate of climb indicator provides no usable information during this climb.
34. Nav. sets revised data into computer. Therefore, shouldn't Nav. "receive and acknowledge" same? Nav. could verbally provide pilot with info.
35. Follows PND
36. Assumed still on full A/B. No throttle changes.
39. During climb mach and heading will be monitored. Status panel and subsystems will be scanned; "press to test" outputs can be checked
41. Throttle retard adjustments will be necessary to maintain M as fuel wgt. is used.
42. From (42) to (44) he is closely monitoring PND. A five second delay in responding to offset turn signal will put him (X) miles beyond offset point
44. Information is put into computer by Nav. At this point his fuel gage reads just over 1/3 of original amount. Knowing he has not yet combatted at M Z for 3 min. this might cause undue concern about range.
48. Nav. detects target on scope.
49. What is information IFF response gives pilot about real identity of target?
50. Did bogey fail to respond because of lack of or malfunctioning IFF equip.; or is he an enemy A/C? Assumed at this point that pilot knows he has sufficient fuel to make identification pass.
51. Learns that Nav. has just locked on target and momentarily disrupted signal to radar.
55. "Size of target" and approx. location will ease task of spotting by providing useful mental set to pilot. Easier and more effective than random search activity. What does range info (miles) means to pilot? Is it translated to "time-to-go" or "size of target"?

59. At this point ident. of target might be complete by recognizing shape of known enemy A/C in which case ident. approach is stopped.
62. Passes target at kts (assuming tgt speed = M) or ft/sec. It is questionable that Id. Nos. could be read at that speed. (What is ident. procedure at night?) Will probably be necessary to throttle back to reduce rate of closure for reading Id. Nos.
67. Does pilot translate "range" to "time"
70. Scans eng. instruments and status panel during this time.
72. A/C reaches command heading.
75. If no ECM are observed the mission will continue as detailed. If ECM is encountered, the Nav/AI will have a job of high speed interpretation and decision making. The pilot will be receiving info. from the Nav/AI about the ECM, but there are only two points during all the possible ECM when a pilot decision might be necessary, indicated under "Pilot Action" by (*).
79. Nav. has positioned target designator and locked on: he informs pilot.
83. Nav. tells pilot that large decoy is homing in.
86. From item (80) there are 3 pts at which pilot may have to decide to attack or ignore decoy. At 12 secs, 30 secs, or 32 secs at which pt he decides, is determined by when Nav finds out the homing decoy exists.
87. 43 secs from item (80) pilot may have to decide to use optical ranging.
89. Missiles weigh pounds,
90. If extreme high "G" breakaway is carried out pilot will probably be unable to see missile trail and by the time the missile gets to target the interceptor will be turned such that the target may be out of line of sight.
91. At night he may never see target. Ground radar or Nav/AI may have to determine strike.
94. ADF, vocal heading from Nav, GCI and TACAN can supply direction-to-base information.
96. A/C has been at Mach for 10.33 minutes (excerpt from: Electrical systems; No.: Para 1.2.4.2 Endurance at maximum speed: 10 minutes @ M based on 15 min. cruise out at M and fuel temp limitations at the engine inlet at F.) Is this exceeded limit critical: Does pilot use % thrust to make initial throttle setting for cruise or throttle position? Or: would he retard throttle below cruise setting and use dive energy plus momentum to maintain speed until cruise alt. is reached (at which point he advances throttle to cruise setting)?
108. Status panel or knee clipboard.
109. Gradual descent from
110. Landing check-off list could be presented by status panel.
112. Watching outside cockpit for other A/C in the area. What is prescribed descent pattern from
113. What provides pilot with range to end of runway) (radio markers)?
115. Speed brakes assumed necessary.
121. Intermittent throttle adjustments are made throughout approach.
124. At this pt. pilot closely observes sides of runway rising in his view to establish proper T.D. attitude at proper moment he cuts engines to idle.

125. Lands with 5+ min. fuel remaining. Will pilot use FDAI to establish touch down attitude? Will pilot use stick or brake chute to pivot nose to ground?
126. Pilot will feel decelleration jolt when brake parachute opens.
132. Pilot and loading crew. This check is done after loading crew has rearmed A/C.

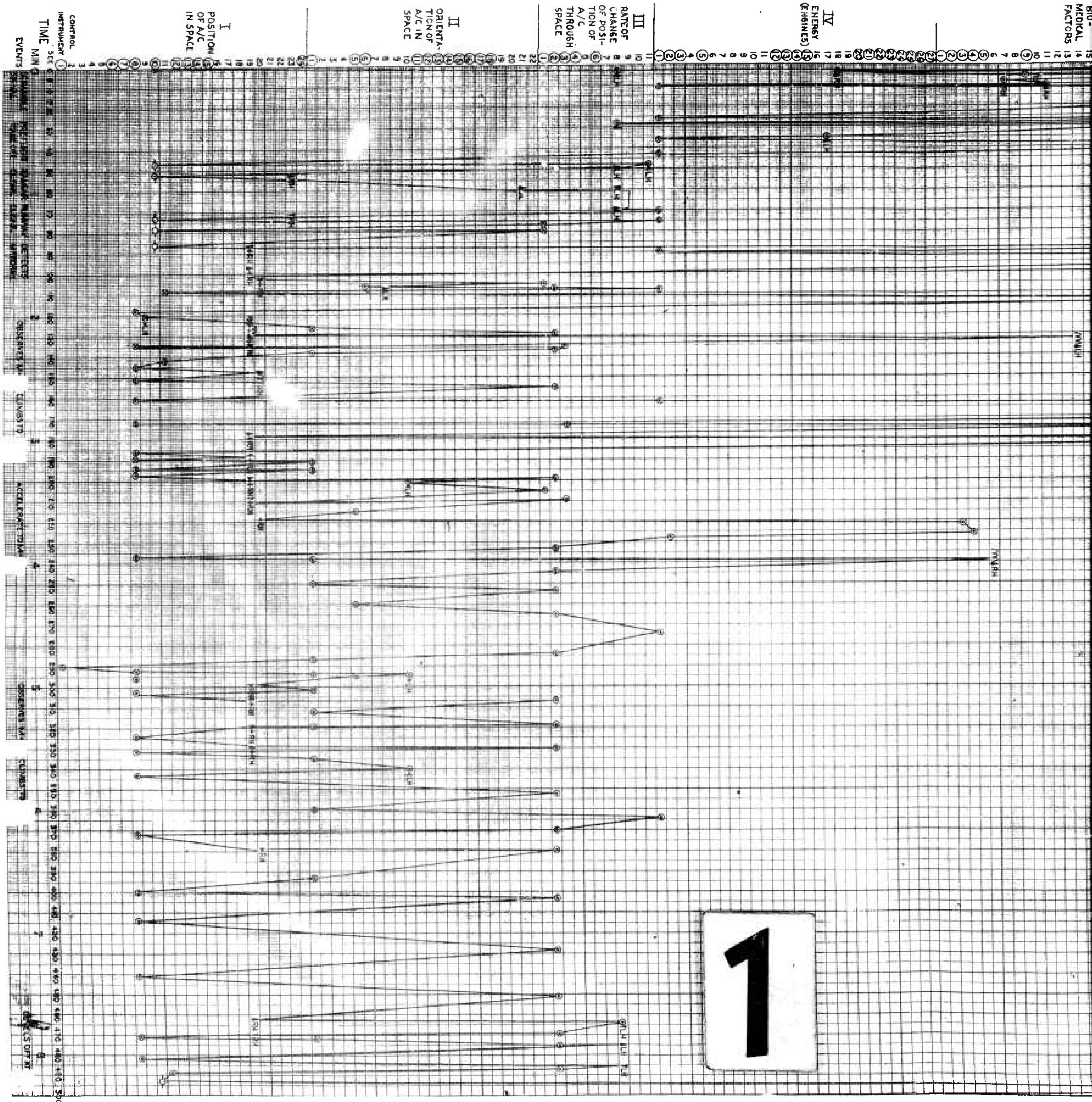
*pounds added with new missile pack.

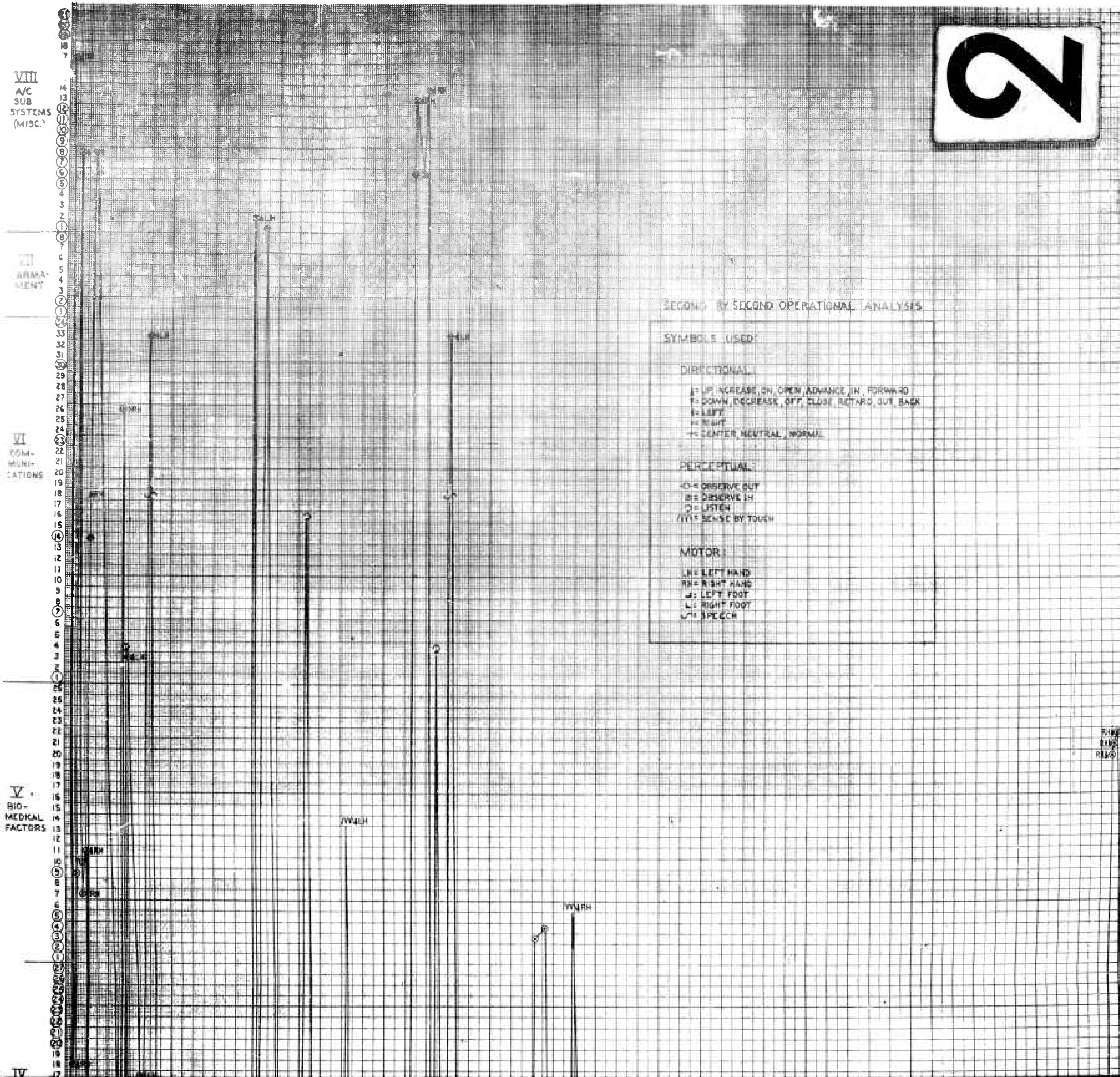
134. Further operations at duty runway include: A/C will have to be refueled and re-"oxygened" equip. Confidence checks will have to be made within the A/C, and the aircrew will probably be changed. To meet the spec., "turn around time shall not exceed five minutes," it will be necessary to complete these servicing operations while the re-arming is being done.

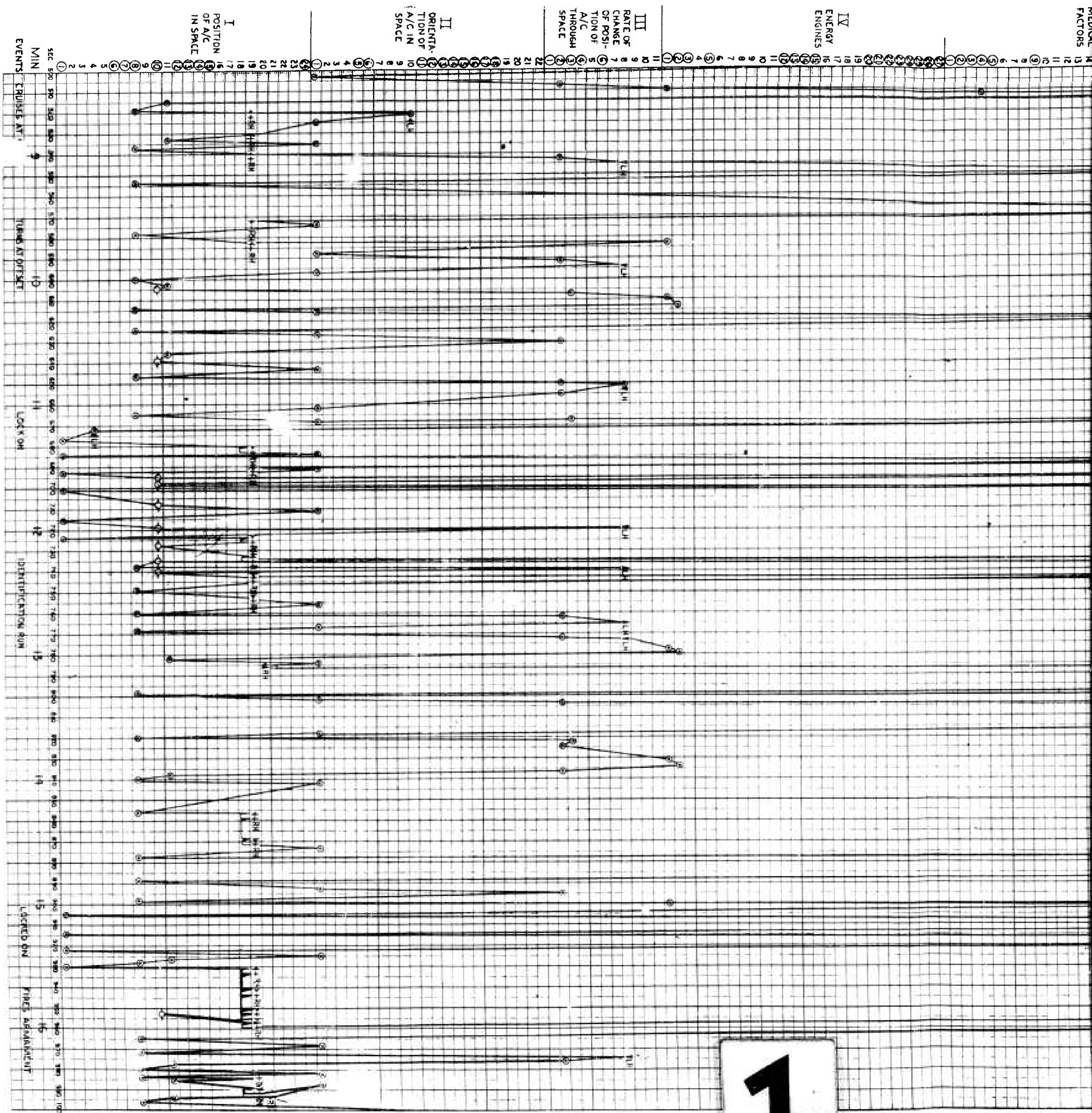
# APPENDIX B

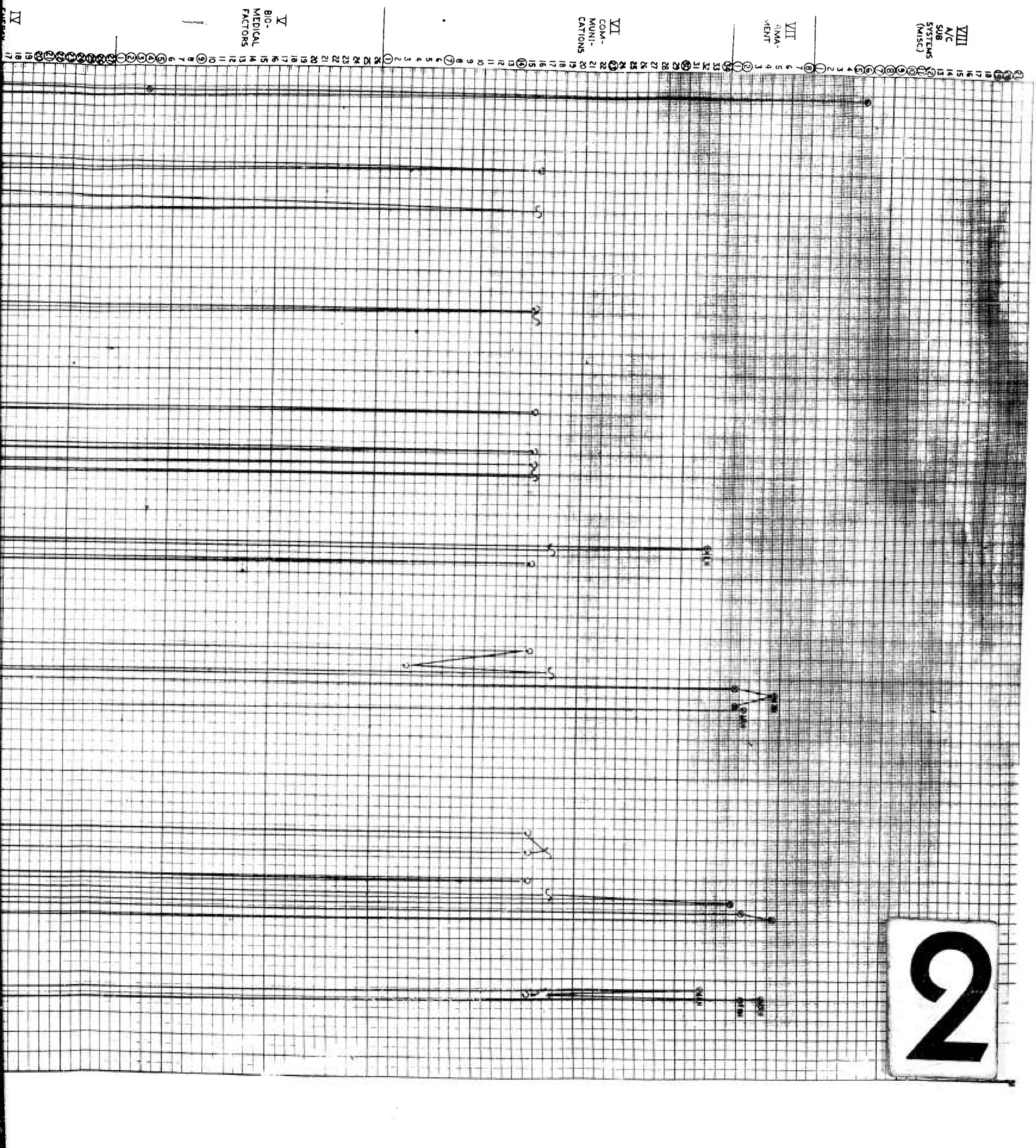
## SECOND BY SECOND OPERATIONAL ANALYSIS

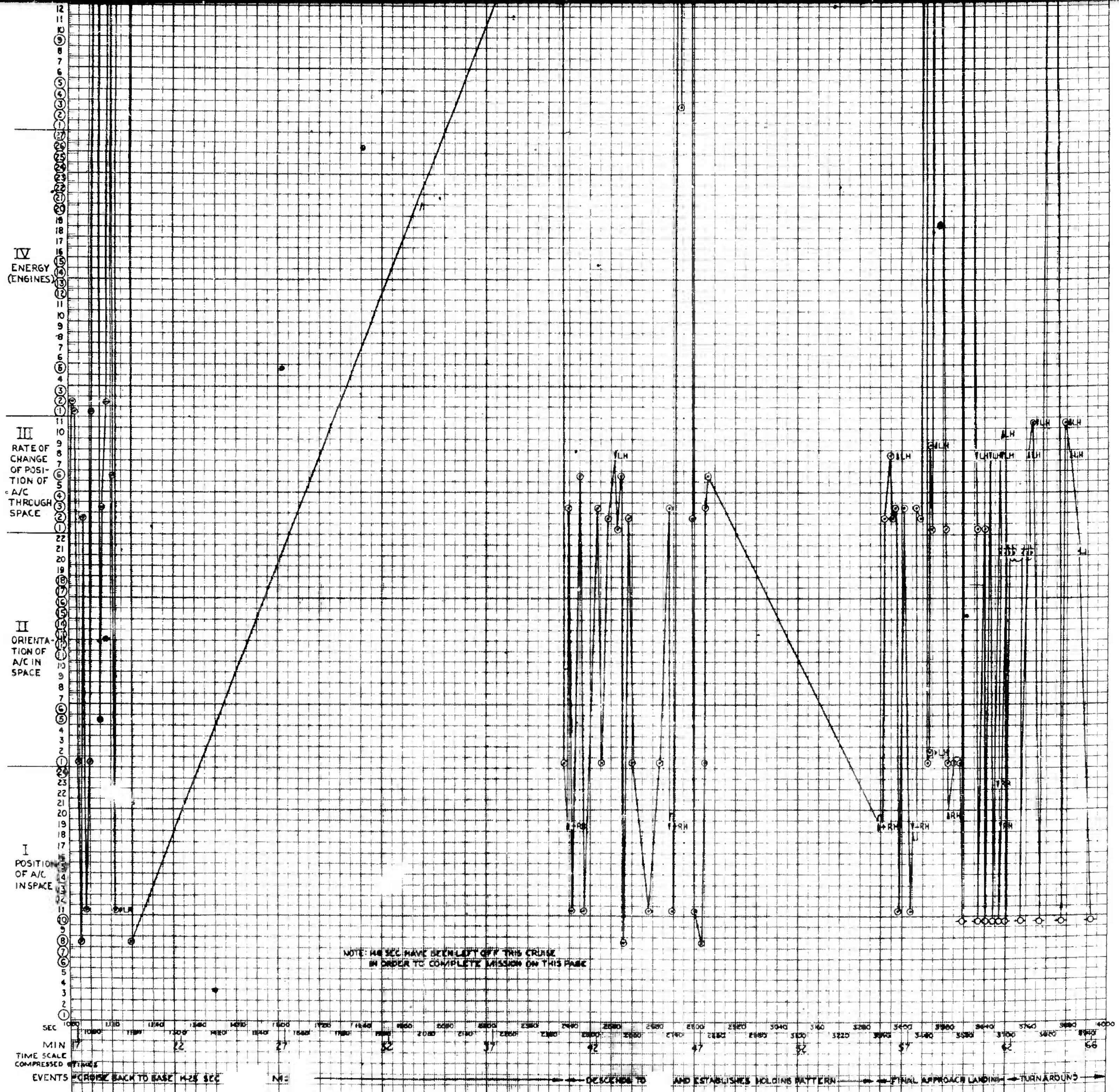
## FOR THE PHASE II AIRCRAFT

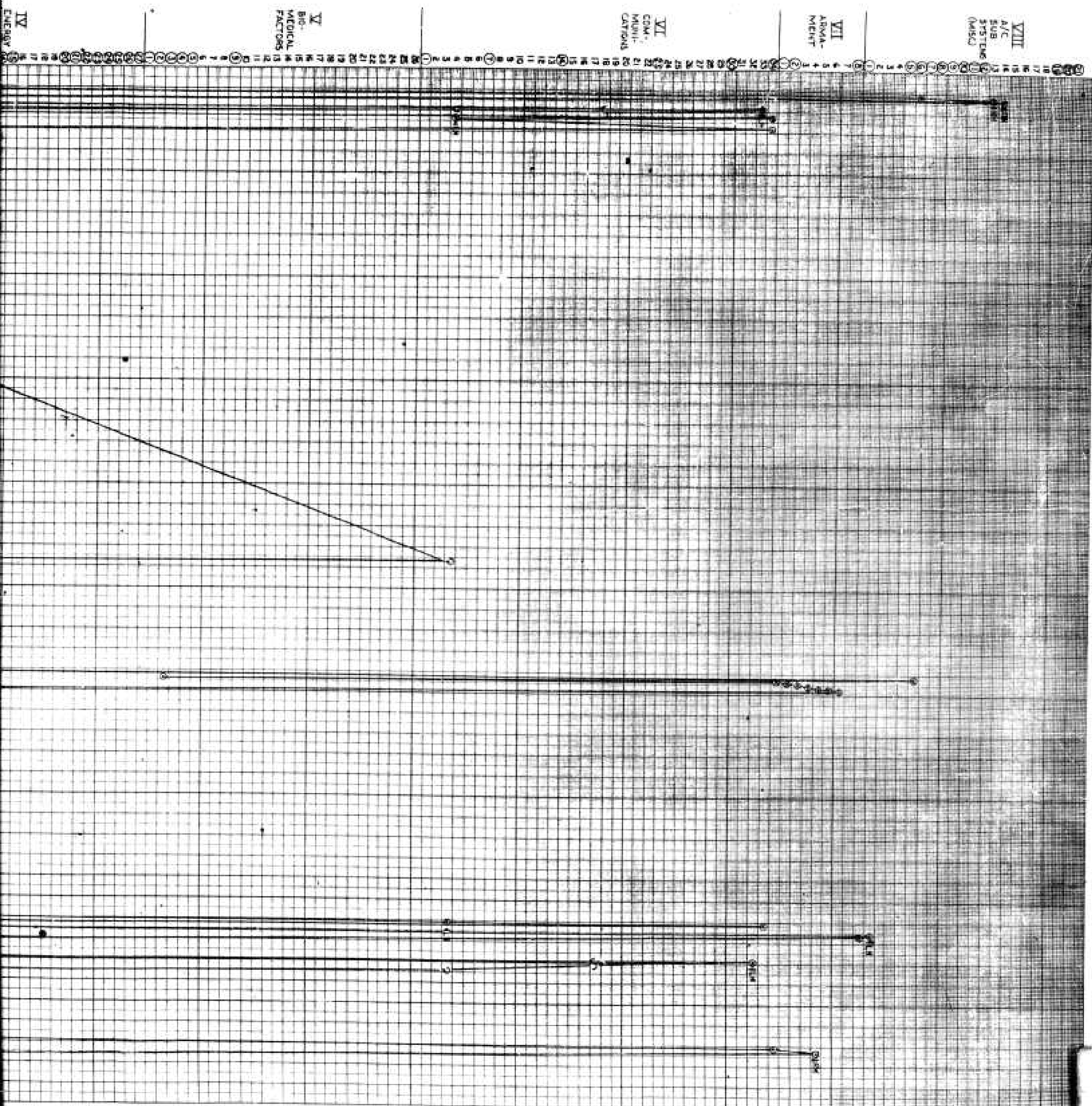

CONTROL INSTRUMENT
TIME
I POSITION OF A/C IN SPACE
II ORIENTATION OF A/C IN SPACE
III RATE OF CHANGE OF POSITION OF A/C THROUGH SPACE
IV ENERGY (ENGINES)
BIO-MEDICAL FACTORS
1


VIII A/C SUB SYSTEMS (MISC.)
VII ARMAMENT
VI COMMUNICATIONS
V BIO-MEDICAL FACTORS
IV
2
SECOND BY SECOND OPERATIONAL ANALYSIS
SYMBOLS USED:
DIRECTIONAL:
= UP, INCREASE, ON, OPEN, ADVANCE, IN, FORWARD
= DOWN, DECREASE, OFF, CLOSE, RETARD, OUT, BACK
= LEFT
= RIGHT
= CENTER, NEUTRAL, NORMAL
PERCEPTUAL:
= OBSERVE OUT
= OBSERVE IN
= LISTEN
= SENSE BY TOUCH
MOTOR:
LH= LEFT HAND
RH= RIGHT HAND
= LEFT FOOT
= RIGHT FOOT
= SPEECH


I POSITION OF A/C IN SPACE
II ORIENTATION OF A/C IN SPACE
III RATE OF CHANGE OF POSITION OF A/C THROUGH SPACE
IV ENERGY ENGINES
MEDICAL FACTORS
EVENTS
MIN
SEC
CRUISES AT
TURNS AT OFFSET
LOCK ON
IDENTIFICATION RUN
LOCKED ON
FIRES ARMAMENT


IV
V BIO-MEDICAL FACTORS
VI COM-MUNI-CATIONS
VII
VIII A/C SUB SYSTEMS (MISC.)
2


I
POSITION OF A/C IN SPACE
II
ORIENTATION OF A/C IN SPACE
III
RATE OF CHANGE OF POSITION OF A/C THROUGH SPACE
IV
ENERGY (ENGINES)
NOTE: 148 SEC HAVE BEEN LEFT OFF THIS CRUISE
IN ORDER TO COMPLETE MISSION ON THIS PAGE
SEC
MIN
TIME SCALE COMPRESSED
EVENTS
CRUISE BACK TO BASE
DESCENDS TO
AND ESTABLISHES HOLDING PATTERN
FINAL APPROACH LANDING
TURNAROUND
LH
RH


IV ENERGY
V BIO-MEDICAL FACTORS
VI COM-MUNI-CATIONS
VII ARMA-MENT
VIII A/C SUB SYSTEMS (MISC)

# APPENDIX C

## PERCEPTUAL AND MOTOR INFORMATIONAL ANALYSIS FOR PHASE II AIRCRAFT

**NOTES:**

(Double line indicates ten seconds elapsed.)

1. Equiprobable range = 30 - 70% thrust (assumed), to 4% accuracy = 10 choices = 3.32 bits. An additional 6.32 bits of information is provided with other proposed engine instuments, the possible choices being increased from 30 to $2^{12.8}$ which necessitates an increase in pilot fixation time of 1.26 seconds (at maximum information input to the pilot of 5 B/S) every time the EPI's are used.

2. Computed separately, two choices on IFF: (a) find correct dial out of six possibilities (2.59 B.) and finding correct setting out of five possibilities (2.32 B.) = 4.901 B = "n" of 30 (H. = $\log_2$ n), therefore, the product of the possible choices (6 x 5) for a two-level decision is equal to the sum of the separate informational values of each level.

3. Receives verbal communication, type of intercept (n = 3, H = 1.58), Cmd. heading (n = 360, H = 8.49) and altitude, (last two digits = 0 and are certain, first 3 digits provide: 5 x 10 x 10 = 500 = n, H = 9). Total H = 19.07 at 5 B/S = 3.8 seconds. (Assuming a redundancy factor of 75% which is increased by message repetition to 87.5% - the message duration becomes an actual 22.84 seconds - this extends into the next two ten-second intervals.) Optimum sampling by the pilot is assumed which would equal 3.8 seconds (spread proportionately over the three ten-second intervals).

   A. Acknowledges message: intcpt: 1.58 B., + HDNG (8.49 B) = 10.07, + Alt. (9 B) = 19.07 bits at 5 B/S = 3.814 seconds x (R-F.) 3 = 11.442. Assumed: perceptual attention required only for nonredundant part of message, therefore = 3.814 seconds spread over two ten-second intervals since actual duration exceeds ten seconds.

4. Pilot is steering A/C down the runway for 8 seconds; 5 B/S input from the external environment, therefore 40 bits.

   B. The control time with the stick is based on studies with pilots using the normal A/C stick. The average for a major stick movement is 1.3 seconds; a secondary movement took 0.4 second.

5. In range M = A to B, there are 8 calibrations, read to the nearest 1/5 of a calibration, therefore 5 x 8 = 40 = n.

6. "OBS to Pilot" = n = 2, H = 1, + "IDD OPERATING", (n = 4, H = 2) = 3 bits at 5 B/S 0.6 second.

7. Choice of one out of six represents a check orientation look at FDAI.

8. First "press to test O2" is located perceptually (2 = n, H = 1) then feedback is observed (2 choices, 1 B.)

9. Ground to INTCEPT.X = 2B, + corrected. Hdng. (2B.) = $4^B$, + XYZ° (360 = n, H = 8.49) = 12.49, + Alt. (1) = 13.49, + XYZ' (270 = n, H = 8.08) = 21.57 = total bits at 5 B/S = 4.314 seconds.

10. Finds and pushes "PRESS-TALK" button = 1 bit +, pilot acknowledges: "Hdng (1B) = 2,XYZ' (8.08) = 19.57 = Total bits,at 5B/S = 4.01 second.

11. Pilot expects cabin alt. between 0 and 30K', n=30 (to nearest 1,000')

12. To the nearest calibration (20%) = 6 choices + on-off = 2 choices, total n = 8.

14. Check reading: "Equipment on or off"

15. Mach is computed without use of command index. If command were set, the Mach reading would be a 3 choice, 1.58 bit perceptual input of 0.3 second.

16. Having established correct heading, pilot monitors IDD bug: "Am I on or to the left or right of course" therefore, 3 choices, 1.58 bits -

17. Started with WADC Link Study Value of 0.47-second fix time - at 5 bits per second - 2.35 bits, = n = 5, because readings on Alt are not equiprobable events. Holding to the nearest 100 feet over an assumed equiprobable range of 2,000 feet = Accuracy = 20%.

18. Extra transitions and 1-bit inputs are feedback from panel and consoles on pilot's control action.

19. He listens to highly redundant patter (96%) for 4.8 seconds. Tells him direction of turn at offset Pt. and range to offset.

20. Monitors rate of decreasing range over 14 seconds to offset turn - Assumed: Control response is to be made within 0.1 second of arrival.

21. Scans environment for 2 seconds looking for target" or "no-target", therefore, 2 choices, 1 bit (2 seconds - scan assumed).

22. Information: "Target (as distinct from all things which are "non-target" = 2 choices = 1 bit) "detected" (versus "not detected") = 2 choices = 1 bit). Also rcvs: "IFF NEGATIVE". Total = 4 bits, 0.8 second.

23. "Identification Pass" = 2B. at 5 B/S = 0.4 second.

24. OBS. to pilot: RADAR ON = 2 B, FLY DOT = 2 bits, = 4 B. at 5 B/S = 0.8 second.

25. Observes scope to see: "Dimmer, brighter or same" 3 choices.

26. Radar scope provides:

| | | n | H |
|---|---|---|---|
| DOT | Azim. (on above, below) | 3 | 1.58 |
| | Elev. " " " | 3 | 1.58 |
| ATT | Roll (right direct, wrong direct, zero error) | 3 | 1.58 |
| | Pitch " " " | 3 | 1.58 |

at 5 B/S = 1.26 seconds.

27. Information - H
"Target" - 1
"Range" - 1
"X Miles" - 1
3 bits

28. Looks at FDAI to get: "Normal Picture" or "not normal" = 2 choices 1 bit.

29. Pilot detects target at X NM Dist., where a foot target subtends a visual angle of degrees (equivalent to 0.612-inch target at -inch viewing distance). Visual identification is possible at this range.

30. "Tgt. Spotted" = 2 bits + locating press talk sw. = 1 bit.

31. Intcpt. reduces speed from Z at $Z_1$ (= $Z_2$ F/second) to M = $Z_3$ at $Z_4$ k' (= $Z_5$ ft/second). Passes target, reads ID numbers to ground. (A six-digit number is assumed). It is further assumed that pilot cannot identify bogey visually. Six-digit number (10 choice/digit) = $10^6$ = n, therefore, H = 19.92 at 5 B/second 3.984 second.

32. 

| | Bits |
|---|---|
| "OBS to pilot | 1 |
| Range X miles | 2 |
| Rate X miles/min" | 3 |
| | 6 |

at 5 B/S = 1.2

33. "Ground Control to Flt. X" = 2B
Target Hostile = 2
4

at 5 B/S = 0.8

34. One bit to locate knob = 2 ch. + 5 choices on knob (2.32 B) = 3.32 B

36. 

| | BITS |
|---|---|
| OBS to Pilot | 2 |
| Tgt Detected | 2 |
| No ECM | 2 |
| Breakaway Heading | 2 |

X
Y 360 = 8.49
Z

TOTAL 15.5

at 5 B/S = 3.1 seconds X 3 (75% redundant) = 9.3 seconds, repeated once (~~omitting "OBS. to pilot"~~) = 18.2 sconds.

38. Hit or "no-hit". Monitors for 6 seconds to get the information.

39. Finds button -1

"Interceptor X to ground control" -2

"Tgt. destroyed" -2

4

at 5 B/S = 0.8 second

40. OBS to pilot = 2 B, + Base Hdng. (2) = 4 B, + XYZ° (360 = n, H = 8.49) = 12.49 B, at 5 B/S = 2.49 seconds. Spread over two ten-second intervals.

| (a) Minutes Elapsed | (b) Code | (c) Instrument | (d) Accuracy (percent) | (e) Control | (f) Fixation Time (seconds) | (g) Transition Time (seconds) | (h) Reaction Time (seconds) | (i) Control Time (seconds) | (j) Bits of Info. $H_{bits} = \log_2 n$ | (k) "n" = no. of Possible Choices (equiprobable) | (l) Total Bits/ 10-second Interval | (m) Total Time/ 10-sec Interval | (n) % of 10-sec Interval Occupied | (o) Note No. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 1-10 | Ext Environ. | 50 | | 0.2 | 0.3 | | | 1 | 2 | | | | |
| | 3-8 | Throttles | 50 | | 0.2 | 0.3 | | | 1 | 2 | | | | |
| | 3-8 | | | Throttles | | 0.73 | 0.18 | 0.33 | 1 | 2 | | | | |
| | 8-17 | Mast Elec Sw | 50 | | 0.2 | 0.14 | | | 1 | 2 | | | | |
| | 8-17 | | | Mast Elec Sw | | 0.75 | 0.18 | 0.15 | 1 | 2 | | | | |
| | 4-18 | Eng. Start | 50 | | 0.2 | 0.14 | | | 1 | 2 | | | | |
| | 4-18 | | | Eng. Start | | 0.34 | 0.18 | 0.15 | 1 | 2 | | | | |
| | 5-9 | Canopy | 50 | | 0.2 | 0.14 | | | 1 | 2 | | | | |
| | 5-10 | | | Canopy Close Off Open | | 0.52 | 0.29 | 0.15 | 1.58 | 3 | | | | |
| | 8-8 | Alternators Fail - L & R | 50 | | 0.2 | 0.14 | | | 1 | 2 | | | | |
| | 5-7 | Air Supply Off On | 50 | | 0.2 | 0.14 | | | 1 | 2 | | | | |
| | 5-7 | | | Air Supply Sw | | 0.34 | 0.29 | 0.15 | 1.58 | 3 | | | | |
| | 5-11 | Manual Canopy Lock | 50 | | 0.2 | 0.14 | | | 1 | 2 | | | | |
| | 5-11 | | | Manual Canopy Lock | | 0.72 | 0.18 | 0.15 | 1 | 2 | 15.16 | 8.82 | 88.2 | |
| | 4-1 | EPI (2) | 4, 33 | | 1.3 | 0.28 | | | 6.48 | 89 | | | | |
| | 8-8 | Alt Fail L & R | 50 | | 0.2 | 0.14 | | | 1 | 2 | | | | |

| (a) | (b) | (c) | (d) | (e) | (f) | (g) | (h) | (i) | (j) | (k) | (l) | (m) | (n) | (o) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 6-14 | Intercom | 16.5 | | 0.52 | 0.14 | | | 2.6 | 6 | | | | |
| | 6-18 | | | Intcm Cntrl pnl comm. Sw | | 0.72 | 0.18 | 0.15 | 1 | 2 | 11.08 | 3.63 | 36.3 | |
| | 4-1 | EPI (2) | 4, 33 | | 1.3 | 0.28 | | | 6.48 | 89 | | | | |
| | 6-26 | IFF | 16.5, 20 | | 0.98 | 0.14 | | | 4.9 | 30 | | | | 2 |
| | 6-26 | | | Off-standby Low-Nor. Emer. | | 0.75 | 0.49 | 0.15 | 2.32 | 5 | | | | |
| | 3-8 | Throttles | 50 | | 0.2 | 0.14 | | | 1 | 2 | | | | |
| | 3-8 | | | Throttles | | 0.73 | 0.25 | 0.36 | 1 | 2 | | | | |
| | 6-4 | UHF(Listens) | 87.5 | | 1.7 | 0.14 | | | 8.5 | $2^{8.5}$ | 24.12 | 7.61 | 76.1 | 3 |
| | 6-18 | UHF (Listens) | | | 1.7 | | | | 8.5 | $2^{8.5}$ | | | | |
| | 6-3 | UHF Volume | 50 | | 0.2 | 0.14 | | | 1 | 2 | | | | |
| | 6-3 | | 20 | UHF Volume | | 0.72 | 0.65 | 0.15 | 3.32 | 10 | | | | |
| | 4-17 | Eng. Fuel Sw | 50 | | 0.2 | 0.14 | | | 1 | 2 | | | | |
| | 4-17 | | 50 | Norm-Emer. | | 0.57 | 0.18 | 0.15 | 1 | 2 | | | | |
| | 5-1 | EPI (2) | 4, 33 | | 1.3 | 0.28 | | | 6.48 | 89. | 21.3 | 6.38 | 63.8 | |
| | 6-33 | Press-talk Sw | 50 | | 0.2 | 0.14 | | | 1 | 2 | | | | |
| | 6-33 | | 50 | Press-talk | | 0.15 | 0.18 | 0.15 | 1 | 2 | | | | |
| | 6-18 | | | UHF Talks | | 0 | 0.18 | 3.43 | 17.17 | $2^{19}$ | | | | A |
| | | UHF Listens | | | 0.4 | | | | 2.04 | | | | | |
| | 4-1 | EPI (2) | 4, 33 | | 1.3 | 0.28 | | | 6.48 | 89 | | | | |
| | 1-10 | Ext Env | 50 | | 0.2 | 0.3 | | | 1 | 2 | 28.69 | 6.91 | 69.1 | |
| | 3-11 | Parking Brk | 50 | | 0.2 | 0.3 | | | 1 | 2 | | | | |
| | 3-11 | | 50 | Park Brk | | 0.65 | 0.18 | 0.33 | 1 | 2 | | | | |
| | 6-18 | | | UHF Talks | | | | 0.38 | 1.9 | | | | | |
| | 1-10 | Ext Env | | | 4.98 | 0.3 | | | 40 | $2^{[illegible]}$ | | | | 4 |

| (a) | (b) | (c) | (d) | (e) | (f) | (g) | (h) | (i) | (j) | (k) | (l) | (m) | (n) | (o) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 3-8 | | | Throttles | | 0.46 | 0.18 | 0.25 | 1 | 2 | | | | |
| | 1-23 | | | Nose Wh Str | | 0 | 0.49 | 0.15 | 2.32 | 5 | | | | |
| | 3-8 | | | Throttles | | 0 | 0.18 | 0.19 | 1 | 2 | | | | |
| =1 | 2-21 | | | Rudder Brk Pedals | | 0 | 0.38 | 0.4 | 1.58 | 3 | 49.8 | 10. | 100. | |
| | 3-8 | | | Throttles | | 0 | 0.18 | 0.19 | 1 | 2 | | | | |
| | 4-1 | EPI | 4, 33 | | 1.3 | 0.28 | | | 6.48 | 89 | | | | |
| | 1-10 | Ext Env | 66 | | 7.75 | 0.3 | | | 45. | $2^{45}$ | 46.23 | 10. | 100. | |
| | 1-23 | Nosewhl Str | | | | 0 | 0.38 | 0.4 | 1.58 | 3 | | | | |
| | 5-1 | EPI | 4, 33 | | 1.3 | 0.28 | | | 6.48 | 89 | | | | |
| | 3-1 | IAS | 14 | | 0.56 | 0.14 | | | 2.8 | 7 | | | | |
| | 1-10 | Ext Env | | | 5. | 0.3 | | | 25. | $2^{25}$ | | | | |
| | 3-1 | IAS | 5 | | 0.86 | 0.3 | | | 4.3 | 20 | 40.16 | 9.52 | 95.2 | |
| | 1-10 | Ext Env | | | 1.0 | 0.3 | | | 5 | $2^{5}$ | | | | |
| | 1-19 | | | Cntrl Stick | | 0 | 0.75 | 1.7 | 4 | 16 | | | | B |
| | 8-2 | Lnd Gr Cntrl | 50 | | 0.2 | 0.3 | | | 1 | 2 | | | | |
| | 8-2 | | 50 | Lnd Gr Cntrl | | 0.75 | 0.18 | 0.19 | 1 | 2 | | | | |
| | 4-1 | EPI | 4, 33 | | 1.3 | 0.28 | | | 6.48 | 89 | 17.48 | 6.95 | 69.5 | |
| | 8-1 | Lnd Gr Pos Ind | 33 | | 0.32 | 0.14 | | | 1.58 | 3 | 1.58 | 0.46 | 4.6 | |
| | 1-19 | | | Stick | | 0 | 0.75 | 1.7 | 4 | 16 | | | | |
| | 1-20 | | | Trim Button | | 0 | 0.18 | 0.1 | 1 | 2 | | | | |
| | 3-1 | IAS | 5 | | 0.86 | 0.14 | | | 4.3 | 20 | | | | |
| | 2-6 | Damper panel | 50 | | 0.2 | 0.14 | | | 1 | 2 | | | | |
| | 2-7 | | | Damper Pwr Sw | | 0.55 | 0.38 | 0.1 | 1.58 | 3 | | | | |
| | 3-2 | Mach | 2.5 | | 1.06 | 0.14 | | | 5.3 | 40 | | | | 5 |
| | 4-1 | EPI | 4, 33 | | 1.3 | 0.28 | | | 6.48 | 89 | | | | |

| (a) | (b) | (c) | (d) | (e) | (f) | (g) | (h) | (i) | (j) | (k) | (l) | (m) | (n) | (o) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1-11 | Alt | 5 | | 1.53 | 0.14 | | | 7.64 | 200 | 31.30 | 9.55 | 95.5 | |
| | 6-16 | Intercom (listen) | 87.5 | | 0.6 | 0.14 | | | 3.0 | 8 | | | | |
| 2 | 1-8 | IDD | 33, 10 | | 0.98 | 0.14 | | | 4.91 | 30 | 7.91 | 1.86 | 18.6 | |
| | 1-9 | IDD Sel Sw | 50 | | 0.2 | 0.14 | | | 1 | 2 | | | | |
| | 1-9 | | 25 | IDD Sel Sw | | 0.67 | 0.44 | 0.1 | 2. | 4 | | | | |
| | 2-1 | FDAI | 16.5 | | 0.52 | 0.14 | | | 2.58 | 6 | | | | 7 |
| | 3-2 | Mach | 2.5 | | 1.06 | 0.14 | | | 5.3 | 40 | 10.88 | 3.41 | 34.1 | |
| | 1-19 | | | Stick | | 0 | 0.75 | 1.7 | 4 | 16 | | | | |
| | 5-14 | Oxy Press Test | 50 | | 0.2 | 0.14 | | | 1 | 2 | | | | 8 |
| | 5-14 | | 50 | Oxy Press Test | | 0.74 | 0.18 | 0.25 | 1 | 2 | | | | |
| | 1-19 | | | Stick | | 0 | 0.75 | 1.7 | 4 | 16 | | | | |
| | 1-8 | IDD | 33, 10 | | 0.98 | 0.14 | | | 4.91 | 30 | | | | |
| | 3-3 | Rate/Climb | 33 | | 0.32 | 0.14 | | | 1.58 | 3 | | | | |
| | 3-2 | Mach | 5 | | 0.86 | 0.14 | | | 4.3 | 20 | | | | |
| | 2-1 | FDAI | 16.5 | | 0.52 | 0.14 | | | 2.58 | 6 | 23.37 | 9.65 | 96.5 | |
| | 1-11 | Alt | 5 | | 1.53 | 0.14 | | | 7.64 | 200 | | | | |
| | 1-8 | IDD | 33, 10 | | 0.98 | 0.14 | | | 4.91 | 30 | 12.55 | 2.79 | 27.9 | |
| | 1-20 | | | Trim Sw | | 0 | 0.18 | 0.1 | 1. | 2 | | | | |
| | 1-8 | IDD | | | 0.98 | 0.14 | | | 4.91 | 30 | | | | |
| | 3-2 | Mach | 5 | | 0.86 | 0.14 | | | 4.3 | 20 | | | | |
| | 1-8 | IDD | 33, 10 | | 0.98 | 0.14 | | | 4.91 | 30 | 15.12 | 3.8 | 38 | |
| | 4-1 | EPI | 4, 33 | | 1.3 | 0.28 | | | 6.48 | 89 | | | | |
| | 8-6 | Status Pan. | 50 | | 0.2 | 0.14 | | | 1 | 2 | | | | |
| | 8-13 | Status Pan. Press Test | 50 | | 0.2 | 0.14 | | | 1 | 2 | | | | |

| (a) | (b) | (c) | (d) | (e) | (f) | (g) | (h) | (i) | (j) | (k) | (l) | (m) | (n) | (c) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 8-13 | | 50 | Status Pan. Press Test | | 0.74 | 0.18 | 0.1 | 1 | 2 | | | | |
| | 8-6 | Status Pan. | 50 | | 0.2 | 0.14 | | | 1 | 2 | | | | |
| | 8-14 | Status Pan. Pres Reset | 50 | | 0.2 | 0.14 | | | 1 | 2 | | | | |
| | 8-14 | | 50 | Status Pan. Pres Reset | | 0.55 | 0.18 | 0.1 | 1 | 2 | 12.48 | 4.79 | 47.9 | |
| | 1-8 | IDD | 33, 10 | | 0.98 | 0.14 | | | 4.91 | 30 | | | | |
| | 3-3 | R/C | 33 | | 0.32 | 0.14 | | | 1.58 | 3 | | | | |
| | 6-4 | UHF (Listen) | 87.5 | | 1.72 | 0.14 | | | 8.63 | 28.6 | | | | 9 |
| 3 | 1-19 | | | Stick | | 0 | 0.75 | 1.7 | 4 | 16 | 19.12 | 5.89 | 58.9 | |
| | 6-18 | UHF (Listen) | 75 | | 1.72 | 0 | 0.25 | | 8.63 | 28.6 | | | | |
| | 6-33 | Pres Tlk Sw | 50 | | 0.2 | 0.14 | | | 1 | 2 | | | | 1[illegible] |
| | 6-33 | | 50 | Pres Talk | | 0 | 0.18 | 0.1 | 1 | 2 | | | | |
| | 1-8 | IDD | 33, 10 | | 0.98 | 0.14 | | | 4.91 | 30 | | | | |
| | 1-19 | | | Stick | | 0 | 0.75 | 1.7 | 4 | 16 | | | | |
| | 1-8 | IDD | 33, 10 | | 0.98 | 0.14 | | | 4.91 | 30 | 25.09 | 7.28 | 72.8 | |
| | 2-1 | FDAI | 16.5 | | 0.52 | 0.14 | | | 2.58 | 6 | | | | |
| | 6-18 | UHF Listen | | | 0.86 | | | | 4.32 | 24.3 | | | | |
| | 1-8 | IDD | 33, 10 | | 0.98 | 0.14 | | | 4.91 | 30 | | | | |
| | 2-1 | FDAI | 16.5 | | 0.52 | 0.14 | | | 2.58 | 6 | | | | |
| | 1-8 | IDD | 33, 10 | | 0.98 | 0.14 | | | 4.91 | 30 | | | | |
| | | | | UHF Talk | | | | 1.3 | 6.04 | | | | | |
| | 1-19 | | | Stick | | 0 | 0.75 | 1.7 | 4 | 16 | | | | |
| | 3-2 | Mach | 2.5 | | 1.06 | 0.14 | | | 5.3 | 40 | 34.64 | 9.37 | 93.7 | |
| | 2-10 | Rud Trim | 50 | | 0.72 | 0.14 | | | 3.58 | 12 | | | | |
| | | | | UHF Talk | | | | 2.7 | 12.58 | | | | | |

| (a) | (b) | (c) | (d) | (e) | (f) | (g) | (h) | (i) | (j) | (k) | (l) | (m) | (n) | (o) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2-10 | | | Rud Trim | | 0.65 | 0.18 | 0.1 | 1 | 2 | | | | |
| | 3-1 | IAS | 14 | | 0.56 | 0.14 | | . | 2.8 | 7 | | | | |
| | 1-19 | | | Stick | | 0 | 0.75 | 1.7 | 4 | 16 | | | | |
| | 3-3 | R/C | 33 | | 0.32 | 0.14 | | | 1.58 | 3 | 25.52 | 8.10 | 81.0 | |
| | 2-5 | T & S | 16.6 | | 0.52 | 0.14 | | | 2.58 | 6 | 2.58 | 0.66 | 6.6 | |
| | 1-20 | | | Trim Sw | | 0 | 0.18 | 0.1 | 1 | 2 | | | | |
| | 5-3 | Cab Pres Alt | 3.3 | | 0.98 | 0.14 | | | 4.91 | 30 | | | | 11 |
| | 5-4 | Liq Oxy Quant | 20, 50 | | 0.6 | 0.14 | | | 3.0 | 8 | | | | 12 |
| | 4-2 | Fuel (2) | 2 | | 2.24 | 0.28 | | | 11.2 | 211.2 | 20.11 | 4.66 | 46.6 | |
| | 3-2 | Mach | 2.5 | | 1.06 | 0.14 | | | 5.3 | 40 | | | | |
| | 1-8 | IDD | 33, 10 | | 0.98 | 0.14 | | | 4.91 | 30 | | | | |
| | 2-1 | FDAI | 16.5 | | 0.52 | 0.14 | | | 2.58 | 6 | | | | |
| | 5-6 | Air Cond | 50 | | 0.2 | 0.14 | | | 1 | 2 | 13.79 | 3.32 | 33.2 | |
| | 5-6 | | | Air Cond Warm Cool | | 1.11 | 0.38 | 0.2 | 1.58 | 3 | | | | |
| | 3-2 | Mach | 2.5 | | 1.06 | 0.14 | | | 5.3 | 40 | | | | |
| | 2-1 | FDAI | 16.5 | | 0.52 | 0.14 | | | 2.58 | 6 | | | | |
| | 3-2 | Mach | 2.5 | | 1.06 | 0.14 | | | 5.3 | 40 | 14.76 | 4.75 | 47.5 | |
| | 2-5 | T & S | 16.6 | | 0.52 | 0.14 | | | 2.58 | 6 | | | | |
| | 3-2 | Mach | 2.5 | | 1.06 | 0.14 | | | 5.3 | 40 | 7.83 | 1.86 | 18.6 | |
| | 4-1 | EPI (2) | 4, 33 | | 1.3 | 0.28 | | | 6.48 | 89 | 6.48 | 1.58 | 15.8 | |
| | 3-2 | Mach | 2.5 | | 1.06 | 0.14 | | | 5.3 | 40 | 5.3 | 1.20 | 12.0 | |
| | 2-1 | FDAI | 16.5 | | 0.52 | 0.14 | | | 2.58 | 6 | | | | |
| | 1-1 | Radar | 50 | | 0.2 | 0.14 | | | 1. | 2 | 3.58 | 1.00 | 10.0 | 14 |
| | 1-8 | IDD | 33, 10 | | 0.98 | 0.14 | | | 4.91 | 30 | | | | |
| | 2-1 | FDAI | 16.5 | | 0.52 | 0.14 | | | 2.58 | 6 | | | | |

| (a) | (b) | (c) | (d) | (e) | (f) | (g) | (h) | (i) | (j) | (k) | (l) | (m) | (n) | (o) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2-10 | Rud Trim | 50 | | 0.72 | 0.14 | | | 3.58 | 12 | | | | |
| | 2-10 | | 50 | Rud Trim | | 0.65 | 0.18 | 0.1 | 1. | 2 | | | | |
| | 2-5 | T & S | 16.6 | | 0.52 | 0.14 | | | 2.58 | 6 | | | | |
| | 1-8 | IDD | 33, 10 | | 0.98 | 0.14 | | | 4.91 | 30 | | | | |
| | 2-10 | Rud Trim | 50 | | 0.72 | 0.14 | | | 3.56 | 12 | | | | |
| | 2-10 | | | Rud Trim | | 0.65 | 0.18 | 0.1 | 1 | 2 | | | | |
| 5 | 1-19 | | | Stick | | 0 | 0.75 | 1.7 | 4 | 16 | 28.12 | 9.59 | 95.9 | |
| | 2-1 | FDAI | 16.5 | | 0.52 | 0.14 | | | 2.58 | 6 | | | | |
| | 1-8 | IDD | 33, 10 | | 0.98 | 0.14 | | | 4.91 | 30 | | | | |
| | 1-19 | | | Stick | | 0 | 0.75 | 1.7 | 4 | 16 | | | | |
| | 3-2 | Mach | 2.5 | | 1.06 | 0.14 | | | 5.3 | 40 | 16.79 | 5.43 | 54.3 | 15 |
| | 2-1 | FDAI | 16.5 | | 0.52 | 0.14 | | | 2.58 | 6 | | | | |
| | 3-2 | Mach | 2.5 | | 1.06 | 0.14 | | | 5.3 | 40 | | | | |
| | 2-1 | FDAI | 16.5 | | 0.52 | 0.14 | | | 2.58 | 6 | | | | |
| | 1-19 | | | Stick | | 0 | 0.75 | 1.7 | 4 | 16 | 14.46 | 4.97 | 49.7 | |
| | 1-8 | IDD | 33 | | 0.32 | 0.14 | | | 1.58 | 3 | 1.58 | 0.46 | 4.6 | 16 |
| | 1-19 | | | Stick | | 0 | 0.75 | 1.7 | 4 | 16 | | | | |
| | 3-2 | Mach | 2.5 | | 1.06 | 0.14 | | | 5.3 | 40 | | | | |
| | 1-8 | IDD | 33 | | 0.32 | 0.14 | | | 1.58 | 3 | | | | |
| | 2-1 | FDAI | 16.5 | | 0.52 | 0.14 | | | 2.58 | 6 | 13.46 | 4.77 | 47.7 | |
| | 2-10 | Rud Trim | 50 | | 0.72 | 0.14 | | | 3.58 | 12 | | | | |
| | 2-10 | | | Rud Trim | | 0.65 | 0.18 | 0.1 | 1 | 2 | | | | |
| | 1-8 | IDD | 33 | | 0.32 | 0.14 | | | 1.58 | 3 | 6.16 | 2.25 | 22.5 | |
| | 3-2 | Mach | 2.5 | | 1.06 | 0.14 | | | 5.3 | 40 | | | | |
| 6 | 2-1 | FDAI | 16.5 | | 0.52 | 0.14 | | | 2.58 | 6 | 7.88 | 1.86 | 18.6 | |

| (a) | (b) | (c) | (d) | (e) | (f) | (g) | (h) | (i) | (j) | (k) | (l) | (m) | (n) | (o) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | DISCONTINUITY - BEGIN 9TH MINUTE | | | | | | | | | | | | |
| | 1-8 | IDD | 33 | | 0.32 | 0.14 | | | 1.58 | 3 | | | | |
| | 3-8 | | | Throttles | | 0 | 0.18 | 0.19 | 1 | 2 | | | | |
| | 3-2 | Mach | 2.5 | | 1.06 | 0.14 | | | 5.3 | 40 | | | | |
| | 1-11 | Alt | 20 | | 0.47 | 0.14 | | | 2.32 | 5 | 10.20 | 2.64 | 26.4 | 17 |
| | 1-10 | Ext Env | 50 | | 0.2 | 0.3 | | | 1 | 2 | | | | |
| | 5-20 | High Alt Lgt | 50 | | 0.4 | 0.44 | | | 2 | 4 | | | | 18 |
| | 5-20 | | | On-Off | | 0.94 | 0.45 | 0.1 | 2 | 4 | | | | |
| | 5-21 | High Alt Lgt Main Panel | 50 | | 0.4 | 0.28 | | | 2 | 4 | | | | |
| | 5-21 | | | Main Panel On-Off | | 0.4 | 0.29 | 0.4 | 1 | 2 | | | | |
| | 5-22 | High Alt Lgt Consoles | 50 | | 0.4 | 0.28 | | | 2 | 4 | | | | |
| | 5-22 | | | Consoles On-Off | | 0.4 | 0.29 | 0.4 | 1 | 2 | 11.0 | 6.37 | 63.7 | |
| | 2-1 | FDAI | 16.5 | | 0.52 | 0.14 | | | 2.58 | 6 | | | | |
| | 3-2 | Mach | 2.5 | | 1.06 | 0.14 | | | 5.3 | 40 | 7.88 | 1.86 | 18.6 | |
| | 4-1 | EPI(2) | 4, 33 | | 1.3 | 0.28 | | | 6.48 | 89 | | | | |
| | 5-4 | LOX Quant | 20, 50 | | 0.6 | 0.14 | | | 3. | 8 | | | | |
| | 8-6 | Status Pnl | 50 | | 0.2 | 0.14 | | | 1 | 2 | | | | |
| | 1-11 | Alt | 20 | | 0.47 | 0.14 | | | 2.32 | 5 | | | | |
| | 1-8 | IDD | 33 | | 0.32 | 0.14 | | | 1.58 | 3 | | | | |
| | 1-19 | | | Stick | | 0 | 0.75 | 0.17 | 4 | 16 | 18.38 | 6.18 | 61.8 | |
| | 2-10 | Rud Trim | 50 | | 0.2 | 0.14 | | | 1 | 2 | | | | |
| | 2-10 | | | Rud Trim | | 0.65 | 0.18 | 0.1 | 1 | 2 | | | | |
| | 2-1 | FDAI | 16.5 | | 0.52 | 0.14 | | | 2.58 | 6 | 4.58 | 1.93 | 19.3 | |

| (a) | (b) | (c) | (d) | (e) | (f) | (g) | (h) | (i) | (j) | (k) | (l) | (m) | (n) | (o) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1-19 | | | Stick | | 0 | 0.75 | 1.7 | 4 | 16 | | | | |
| | 1-11 | Alt | 20 | | 0.47 | 0.14 | | | 2.32 | 5 | | | | |
| | 2-1 | FDAI | 16.5 | | 0.52 | 0.14 | | | 2.58 | 6 | | | | |
| | 1-8 | IDD | 33 | | 0.32 | 0.14 | | | 1.58 | 3 | | | | |
| 9 | 1-19 | | | Stick | | 0 | 0.75 | 1.7 | 4 | 16 | 14.48 | 6.63 | 66.3 | |
| | 3-2 | Mach | 2.5 | | 1.06 | 0.14 | | | 5.3 | 40 | | | | |
| | 3-8 | | | Throttles | | 0 | 0.18 | 0.19 | 1 | 2 | | | | |
| | 6-16 | Intercom | 96 | | 4.8 | 0.14 | | | 4 | 16 | 10.3 | 6.51 | 65.1 | 19 |
| | 1-8 | IDD | 0.1 | | 9.86 | 0.14 | | | 50 | $2^{50}$ | 50.00 | 10 | 100 | 20 |
| | 6-16 | | 87.5 | Intcm (Talks) | | 0 | 0.18 | 0.6 | 3 | 8 | 3.00 | 0.78 | 7.8 | |
| | 1-19 | | | Stick | | 0 | 0.75 | 1.7 | 4 | 16 | | | | |
| | 2-1 | FDAI | 16.5 | | 0.52 | 0.14 | | | 2.58 | 6 | | | | |
| | 1-19 | | | Stick | | 0 | 0.75 | 1.7 | 4 | 16 | | | | |
| | 1-8 | IDD | 0.7 | | 4.0 | 0 | | | 20 | $2^{20}$ | | | | |
| | 1-19 | | | Stick | | 0 | 0.75 | 1.7 | 4 | 16 | 34.58 | 9.56 | 95.6 | |
| | 4-1 | EPI (2) | 4, 33 | | 1.3 | 0.28 | | | 6.48 | 89 | | | | |
| | 2-1 | FDAI | 16.5 | | 0.52 | 0.14 | | | 2.58 | 6 | 9.06 | 2.24 | 22.4 | |
| | 3-2 | Mach | 2.5 | | 1.06 | 0.14 | | | 5.3 | 40 | | | | |
| | 3-8 | | | Throttles | | 0 | 0.18 | 0.19 | 1 | 2 | | | | |
| | 2-1 | FDAI | 16.5 | | 0.52 | 0.14 | | | 2.58 | 6 | | | | |
| 10 | 1-8 | IDD | 33 | | 0.32 | 0.14 | | | 1.58 | 3 | 10.46 | 2.69 | 26.9 | |
| | 1-11 | Alt | 20 | | 0.47 | 0.14 | | | 2.32 | 5 | | | | |
| | 1-10 | Ext Env | 50 | | 2.0 | 0.3 | | | 1 | 2 | | | | |
| | 3-3 | R/C | 33 | | 0.32 | 0.3 | | | 1.58 | 3 | | | | 21 |
| | 4-1 | EPI (2) | 4, 33 | | 1.3 | 0.28 | | | 6.4[illegible] | 89 | | | | |
| | 4-2 | Fuel (2) | 2 | | 2.24 | 0.2[illegible] | | | 11.2 | $2^{11.2}$ | 22.58 | 7.63 | 76.3 | |

| (a) | (b) | (c) | (d) | (e) | (f) | (g) | (h) | (i) | (j) | (k) | (l) | (m) | (n) | (o) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1-8 | IDD | 33 | | 0.32 | 0.14 | | | 1.58 | 3 | | | | |
| | 2-1 | FDAI | 16.5 | | 0.52 | 0.14 | | | 2.58 | 6 | | | | |
| | 6-16 | Intercm | 87.5 | | 0.8 | 0.14 | | | 4.0 | 16 | 8.16 | 2.06 | 20.6 | 22 |
| | 6-16 | | 87.5 | Intcm (Talks) | | 0 | 0.18 | 0.4 | 2 | 4 | | | | 23 |
| | 1-8 | IDD | 33 | | 0.32 | 0.14 | | | 1.58 | 3 | | | | |
| | 2-1 | FDAI | 16.5 | | 0.52 | 0.14 | | | 2.58 | 6 | | | | |
| | 3-2 | Mach | 2.5 | | 1.06 | 0.14 | | | 5.3 | 40 | 11.46 | 2.90 | 29. | |
| | 1-11 | Alt | 20 | | 0.47 | 0.14 | | | 2.32 | 5 | | | | |
| | 1-10 | Ext Env | 50 | | 2.0 | 0.3 | | | 10.0 | 2 | 12.32 | 2.91 | 29.1 | |
| | 2-1 | FDAI | 16.5 | | 0.52 | 0.3 | | | 2.58 | 6 | | | | |
| | 1-8 | IDD | 33 | | 0.32 | 0.14 | | | 1.58 | 3 | | | | |
| | 3-2 | Mach | 2.5 | | 1.06 | 0.14 | | | 5.3 | 40 | 9.46 | 2.48 | 24.8 | |
| | 3-8 | Throttles | 50 | | 0.2 | 0.14 | | | 1 | 2 | | | | |
| | 3-8 | | | Throttles | | 0 | 0.18 | 0.19 | 1 | 2 | | | | |
| | 3-2 | Mach | 2.5 | | 1.06 | 0.14 | | | 5.3 | 40 | 7.30 | 1.91 | 19.1 | |
| 11 | 201 | FDAI | 16.5 | | 0.52 | 0.14 | | | 2.58 | 6 | | | | |
| | 1-8 | IDD | 33 | | 0.32 | 0.14 | | | 1.58 | 3 | | | | |
| | 2-1 | FDAI | 16.5 | | 0.52 | 0.14 | | | 2.58 | 6 | | | | |
| | 3-3 | R/C | 33 | | 0.32 | 0.14 | | | 1.58 | 3 | | | | |
| | 6-16 | Intcm (Listens) | 84 | | 0.8 | 0.14 | | | 4.0 | 16 | 12.32 | 3.18 | 31.8 | 24 |
| | 1-4 | Radar Inten | 20 | | 0.46 | 0.14 | | | 2.32 | 5 | | | | |
| | 1-4 | | 50 | Rad Intens | | 0.77 | 0.18 | 0.1 | 1 | 2 | | | | |
| | 1-1 | Radar Scope | 33 | | 0.32 | 0.14 | | | 1.58 | 3 | | | | 25 |
| | 1-19 | | | Stick | | 0.77 | 0.75 | 1.7 | 4 | 16 | 8.90 | 5.33 | 53.3 | |
| | 1-19 | | | Stick | | 0 | 0.75 | 1.7 | 4 | 16 | | | | |
| | 2-1 | FDAI | 16.5 | | 0.52 | 0.14 | | | 2.58 | 6 | | | | |

| (a) | (b) | (c) | (d) | (e) | (f) | (g) | (h) | (i) | (j) | (k) | (l) | (m) | (n) | (o) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1-1 | Radar | 33 | | 1.26 | 0.14 | | | 6.32 | 81 | | | | 26 |
| | 6-16 | Intcm (List.) | 84 | | 0.6 | 0.14 | | | 3 | 8 | | | | 27 |
| | 1-19 | | | Stick | | 0 | 0.75 | 1.7 | 4 | 16 | 19.90 | 7.70 | 77.0 | |
| | 2-1 | FDAI | 50 | | 0.2 | 0.14 | | | 1.00 | 2 | | | | 28 |
| | 1-19 | | | Stick | | 0 | 0.75 | 1.7 | 4 | 16 | | | | |
| | 1-1 | Radar | 33 | | 1.26 | 0.14 | | | 6.32 | 81 | | | | |
| | 1-10 | Ext Env | 50 | | 0.2 | 0.3 | | | 1 | 2 | | | | 29 |
| | 6-16 | | 87.5 | Intcm (Talks) | | 0 | 0.18 | 0.6 | 3 | 8 | | | | 30 |
| | 1-10 | Ext Env | 50 | | 0.2 | 0.3 | | | 1 | 2 | 16.32 | 5.97 | 59.7 | |
| | 6-16 | Intercom | 84 | | 0.6 | 0 | | | 3 | 8 | | | | |
| | 1-1 | Radar | 33 | | 1.26 | 0.3 | | | 6.32 | 81 | | | | |
| | 1-10 | Ext Env | 50 | | 0.2 | 0.3 | | | 1 | 2 | 10.32 | 2.66 | 26.6 | |
| | 2-1 | FDAI | 50 | | 0.2 | 0.3 | | | 1 | | | | | |
| | 1-1 | Radar | 33 | | 1.26 | 0.14 | | | 6.32 | 81 | | | | |
| | 1-10 | Ext Env | 50 | | 0.2 | 0.3 | | | 1 | 2 | | | | |
| 12 | 3-8 | | | Throttles | | 0 | 0.18 | 0.19 | 1 | 2 | 9.32 | 2.77 | 27.7 | |
| | 1-1 | Radar | 33 | | 1.26 | 0.3 | | | 6.32 | 81 | | | | |
| | 1-19 | | | Stick | | 0 | 0.75 | 1.3 | 4 | 16 | | | | |
| | 1-19 | | | Stick | | 0 | 0.75 | 0.4 | 4 | 16 | | | | |
| | 1-19 | | | Stick | | 0 | 0.75 | 1.3 | 4 | 16 | | | | |
| | 1-19 | | | Stick | | 0 | 0.75 | 0.4 | 4 | 16 | | | | |
| | 1-10 | Ext Env | 50 | | 0.2 | 0.3 | | | 1 | 2 | 23.32 | 8.46 | 84.6 | |
| | 6-33 | Pres-Talk | 50 | | 0.2 | 0.3 | | | 1 | 2 | | | | |
| | 6-33 | | | Press Tlk Sw | | 0 | 0.18 | 0.1 | 1 | 2 | | | | |
| | 1-10 | Ext Env | 50 | | 3.98 | 0.3 | | | 6 | $2^6$ | | | | |
| | 6-18 | | 84 | Commun (Talks to Gnd.) | | 0 | 0.18 | 3.98 | 19.92 | $10^6$ | | | | 31 |

| (a) | (b) | (c) | (d) | (e) | (f) | (g) | (h) | (i) | (j) | (k) | (l) | (m) | (n) | (o) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1-8 | IDD | 33 | | 0.32 | 0.3 | | | 1.58 | 3 | | | | |
| | 3-8 | | | Throttles | | 0 | 0.18 | 0.19 | 1 | 2 | | | | |
| | 1-10 | Ext Env | 50 | | 0.2 | 0.3 | | | 1 | 2 | | | | |
| | 1-19 | | | Stick | | 0 | 0.75 | 1.3 | 4 | 16 | 35.50 | 8.78 | 87.8 | |
| | 6-16 | Intercm | 84 | | 0.8 | 0.3 | | | 4 | 16 | | | | |
| | 1-8 | IDD | 33 | | 0.32 | 0.14 | | | 1.58 | 3 | | | | |
| | 1-19 | | | Stick | | 0 | 0.75 | 1.7 | 4 | 16 | 9.58 | 4.01 | 40.1 | |
| | 2-1 | FDAI | 16.5 | | 0.52 | 0.14 | | | 2.58 | 6 | | | | |
| | 1-19 | | | Stick | | 0 | 0.75 | 1.7 | 4 | 16 | 6.58 | 3.11 | 31.1 | |
| | 1-8 | IDD | 33 | | 0.32 | 0.14 | | | 1.58 | 3 | | | | |
| | 3-2 | Mach | 2.5 | | 1.06 | 0.14 | | | 5.3 | 40 | | | | |
| | 3-8 | | | Throttles | | 0 | 0.18 | 0.19 | 1 | 2 | | | | |
| | 2-1 | FDAI | 16.5 | | 0.52 | 0.14 | | | 2.58 | 6 | | | | |
| | 1-8 | IDD | 33 | | 0.32 | 0.14 | | | 1.58 | 3 | 12.04 | 3.15 | 31.5 | |
| | 3-2 | Mach | 2.5 | | 1.06 | 0.14 | | | 5.3 | | | | | |
| | 3-8 | | | Throttles | | 0 | 0.18 | 0.19 | 1 | 2 | | | | |
| | 4-1 | EPI | 4, 33 | | 1.3 | 0.28 | | | 6.48 | 89 | | | | |
| | 4-2 | Fuel (2) | 2 | | 2.24 | 0.28 | | | 11.2 | 211 | 23.98 | 5.67 | 56.7 | |
| =13 | 1-11 | Alt | 20 | | 0.47 | 0.14 | | | 2.32 | 5 | | | | |
| | 2-1 | FDAI | 16.5 | | 0.52 | 0.14 | | | 2.58 | 6 | | | | |
| | 1-20 | | | Trim Sw | | 0 | 0.18 | 0.1 | 1 | 2 | | | | |
| | 2-1 | FDAI | 16.5 | | 0.52 | 0.14 | | | 2.58 | 6 | | | | |
| | 1-20 | | | Trim Sw | | 0 | 0.18 | 0.1 | 1 | 2 | | | | |
| | 6-16 | Intcm (List.) | 87.5 | | 1.2 | 0.14 | | | 6.0 | 64 | 15.48 | 3.83 | 38.3 | 32 |
| | 6-4 | Arc-52 UHF (Listen) | 87.5 | | 0.8 | 0.14 | | | 4. | 24 | | | | 33 |
| | 6-18 | | | Intcm (Talks) | | 0 | 0.18 | 0.8 | 4 | 24 | | | | |

| (a) | (b) | (c) | (d) | (e) | (f) | (g) | (h) | (i) | (j) | (k) | (l) | (m) | (n) | (o) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1-18 | IDD | 33 | | 0.32 | 0.14 | | | 1.58 | 3 | 9.58 | 2.38 | 23.8 | |
| | 2-1 | FDAI | 16.5 | | 0.52 | 0.14 | | | 2.58 | 6 | | | | |
| | 3-2 | Mach | 2.5 | | 1.06 | 0.14 | | | 5.3 | 40 | | | | |
| | 7-2 | Armt Avail. | 20 | | 0.66 | 0.14 | | | 3.32 | 10 | | | | 34 |
| | 7-6 | Armt Select | 25 | | 0.46 | 0.14 | | | 2.32 | 5 | | | | |
| | 7-6 | | | Armt Select | | 0.66 | 0.44 | 0.25 | 2 | 4 | 15.52 | 4.61 | 46.1 | |
| | 7-2 | Armt Avail. | 20 | | 0.66 | 0.14 | | | 3.32 | 10 | | | | |
| | 7-3 | Arm Sw | 50 | | 0.2 | 0.14 | | | 1 | 2 | | | | |
| | 7-3 | | 50 | Arm Sw | | 0.15 | 0.18 | 0.32 | 1 | 2 | | | | |
| | 2-1 | FDAI | 16.5 | | 0.52 | 0.14 | | | 2.58 | 6 | | | | |
| | 1-8 | IDD | 33 | | 0.32 | 0.14 | | | 1.58 | 3 | 9.48 | 2.91 | 29.1 | |
| | 3-3 | R/C | 33 | | 0.32 | 0.14 | | | 1.58 | 3 | | | | |
| | 3-2 | Mach | 2.5 | | 1.06 | 0.14 | | | 5.3 | 40 | 6.88 | 1.66 | 16.6 | |
| | 4-1 | EPI (2) | 4, 33 | | 1.3 | 0.28 | | | 6.48 | 89 | | | | |
| | 4-2 | Fuel (2) | 2 | | 2.24 | 0.14 | | | 11.2 | $2^{11}$ | | | | |
| | 3-2 | Mach | 2.5 | | 1.06 | 0.14 | | | 5.3 | 40 | | | | |
| | 1-11 | Alt | 20 | | 0.47 | 0.14 | | | 2.32 | 5 | | | | |
| =14 | 1-8 | IDD | 33 | | 0.32 | 0.14 | | | 1.58 | 3 | 26.88 | 6.23 | 62.3 | |
| | 2-1 | FDAI | 16.5 | | 0.52 | 0.14 | | | 2.58 | 6 | | | | |
| | 1-19 | | | Stick | | 0 | 0.75 | 1.7 | 4 | 16 | 6.58 | 3.11 | 31.1 | |
| | 1-8 | IDD | 0.1 | | 9.86 | 0.14 | | | 50 | $2^{50}$ | | | | 20 |
| | 1-19 | | | Stick | | 0 | 0.75 | 1.7 | 4 | 16 | 50.00 | 10. | 100. | |
| | 1-8 | IDD | 0.1 | | 4 | 0 | | | 20 | $2^{20}$ | | | | |
| | 1-19 | | | Stick | | 0 | 0.75 | 1.7 | 4 | 16 | 24.00 | 6.45 | 64.5 | |
| | 2-1 | FDAI | 16.5 | | 0.52 | 0.14 | | | 2.58 | 6 | | | | |

| (a) | (b) | (c) | (d) | (e) | (f) | (g) | (h) | (i) | (j) | (k) | (l) | (m) | (n) | (o) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1-19 | | | Stick | | 0 | 0.75 | 1.7 | 4 | 16 | | | | |
| | 6-16 | Intercm | 87.5 | | 3.1 | 0.14 | | | 15.5 | $2^{15.5}$ | | | | [illegible] |
| | 1-8 | IDD | 33 | | 0.32 | 0.14 | | | 1.58 | 3 | 23.66 | 6.81 | 68.1 | |
| | 6-16 | Intercm | 87.5 | | 0.4 | 0.14 | | | 2.0 | 4 | | | | |
| | 6-18 | | | Intercom (Tlks | | 0 | 0.18 | 0.4 | 2.0 | 4 | | | | |
| | 1-8 | IDD | 33 | | 0.32 | 0.14 | | | 1.58 | 3 | 5.58 | 1.58 | 15.8 | |
| | 2-1 | FDAI | 16.5 | | 0.52 | 0.14 | | | 2.58 | 6 | | | | |
| | 3-2 | Mach | 2.5 | | 1.06 | 0.14 | | | 5.3 | 40 | | | | |
| | 1-8 | IDD | 33 | | 0.32 | 0.14 | | | 1.58 | 3 | | | | |
| | 4-1 | EPI | 4.33 | | 1.3 | 0.28 | | | 6.48 | 89 | 15.94 | 3.90 | 39.0 | |
| 15 | 6-16 | Intercom | 84 | | 0.8 | 0.14 | | | 4.0 | 16 | | | | 24 |
| | 1-1 | Radar | 33 | | 1.26 | 0.14 | | | 6.32 | 81 | 10.32 | 2.34 | 23.4 | |
| | 6-18 | | | Intercom (Talks) | | 0 | 0.18 | 0.8 | 4.0 | 16 | | | | |
| | 7-2 | Armt Avail Sw. | 20 | | 0.66 | 0.14 | | | 3.32 | 10 | | | | |
| | 1-1 | Radar | 33 | | 1.26 | 0.14 | | | 6.32 | 81 | | | | |
| | 7-3 | Arm Sw | 50 | | 0.4 | 0.14 | | | 2 | 4 | | | | |
| | 7-6 | Armt Sel | 25 | | 0.46 | 0.14 | | | 2.32 | 5 | 17.96 | 4.32 | 43.2 | |
| | 1-1 | Radar | 33 | | 1.26 | 0.14 | | | 6.32 | 81 | | | | |
| | 2-1 | FDAI | 16.5 | | 0.52 | 0.14 | | | 2.58 | 6 | | | | |
| | 1-11 | Alt | 20 | | 0.47 | 0.14 | | | 2.32 | 5 | | | | |
| | 1-8 | IDD | 33 | | 0.32 | 0.14 | | | 1.58 | 3 | | | | |
| | 1-19 | | | Stick | | 0 | 0.75 | 1.7 | 4 | 16 | | | | |
| | 1-19 | | | Stick | | 0 | 0.75 | 0.4 | 4 | 16 | | | | |
| | 1-1 | Radar | | | 6.73 | 0.14 | | | 33.65 | $2^{33.6}$ | | | | |

| (a) | (b) | (c) | (d) | (e) | (f) | (g) | (h) | (i) | (j) | (k) | (l) | (m) | (n) | (o) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1-19 | | | Stick | | 0. | 0.75 | 0.4 | 4. | 16 | | | | |
| | 1-19 | | | Stick | | 0 | 0.75 | 0.4 | 4 | 16 | 46.45 | 10. | 100. | |
| | 1-1 | Radar | | | 10 | 0 | | | 50 | $2^{50}$ | | | | |
| | 1-19 | | | Stick | | 0 | 0.75 | 1.7 | 4 | 16 | | | | |
| | 1-19 | | | Stick | | 0 | 0.75 | 0.4 | 4 | 16 | | | | |
| | 1-19 | | | Stick | | 0 | 0.75 | 0.4 | 4 | 16 | | | | |
| | 1-19 | | | Stick | | 0 | 0.75 | 0.4 | 4 | 16 | 50.00 | 10. | 100. | |
| | 1-10 | Ext Env | 50 | | 6 | 0.3 | | | 30 | $2^{30}$ | | | | 38 |
| | 1-19 | | | Stick | | 0 | 0.75 | 1.7 | 4 | 16 | 30.00 | 6.3 | 63. | |
| | 6-33 | Press-Talk | 50 | | 0.2 | 0.14 | | | 1 | 2 | | | | |
| | 6-33 | | | Press-Talk | | 0 | 0.18 | 0.1 | 1 | 2 | | | | |
| | 6-18 | | | Intercom (Talks) | | | 0.83 | 0.8 | 4 | 16 | | | | 39 |
| | 6-16 | Intercom (Listens) | 8.75 | | 0.95 | 0.14 | | | 4.72 | $2^{4.7}$ | | | | 4[illegible] |
| | 7-5 | Launcher Retr. | 50 | | 0.2 | 0.14 | | | 1 | 2 | | | | |
| | 7-5 | | | Launch. Retr. | | 0.56 | 0.38 | 0.1 | 1.58 | 3 | | | | |
| | 7-3 | Arm Sw | 50 | | 0.2 | 0.14 | | | 1 | 2 | | | | |
| =16 | 7-3 | | | Arm Sw | | 0.44 | 0.18 | 0.1 | 1 | 2 | 15.30 | 5.78 | 57.8 | |
| | 1-8 | IDD | 33 | | 0.32 | 0.14 | | | 1.58 | 3 | | | | |
| | 6-16 | Intercom | | | 1.55 | | | | 7.77 | | | | | |
| | 2-1 | FDAI | 16.5 | | 0.52 | 0.14 | | | 2.58 | 6 | 11.93 | 2.67 | 26.7 | |
| | 1-8 | IDD | 33 | | 0.32 | 0.14 | | | 1.58 | 3 | | | | |
| | 3-8 | | | Throttles | | 0 | 0.18 | 0.19 | 1 | 2 | | | | |
| | 3-2 | Mach | 2.5 | | 1.06 | 0.14 | | | 5.3 | 40 | | | | |
| | 1-11 | Alt | 20 | | 0.47 | 0.14 | | | 2.32 | 5 | | | | |

| (a) | (b) | (c) | (d) | (e) | (f) | (g) | (h) | (i) | (j) | (k) | (l) | (m) | (n) | (o) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1-8 | IDD | 33 | | 0.32 | 0.14 | | | 1.58 | 3 | 11.78 | 3.10 | 31.0 | |
| | 2-1 | FDAI | 16.5 | | 0.52 | 0.14 | | | 2.58 | 6 | | | | |
| | 1-19 | | | Stick | | 0 | 0.75 | 1.7 | 4 | 16 | | | | |
| | 1-8 | IDD | 33 | | 0.32 | 0.14 | | | 1.58 | 3 | | | | |
| | 1-19 | | | Stick | | 0 | 0.75 | 0.4 | 4 | 16 | | | | |
| | 1-11 | Alt | 20 | | 0.47 | 0.14 | | | 2.32 | 5 | | | | |
| | 1-19 | | | Stick | | 0 | 0.75 | 0.4 | 4 | 16 | | | | |
| | 1-19 | | | Stick | | 0 | 0.75 | 0.4 | 4 | 16 | | | | |
| | 2-1 | FDAI | 16.5 | | 0.52 | 0.14 | | | 2.58 | 6 | | | | |
| | 1-20 | | | Trim Sw | | 0 | 0.18 | 0.1 | 1 | 2 | 26.06 | 8.57 | 85.7 | |
| | 1-11 | Alt | 20 | | 0.47 | 0.14 | | | 2.32 | 5 | | | | |
| | 1-8 | IDD | 33 | | 0.32 | 0.14 | | | 1.58 | 3 | 3.90 | 1.07 | 10.7 | |
| | 4-2 | Fuel (2) | 2 | | 2.24 | 0.28 | | | 11.2 | $2^{11.2}$ | 11.20 | 2.52 | 25.2 | |
| | 4-1 | EPI (2) | 4, 33 | | 1.3 | 0.28 | | | 6.48 | 89 | 6.48 | 1.58 | 15.8 | |

# APPENDIX D

## EVALUATION OF ONR, WADC AND HUGHES SYSTEMS*

*Prepared by Dunlap and Associates, Inc., Stamford, Connecticut
Separate references at end of appendix.

## NAVY

The contact analog display is a radical departure from any current instrument system and thus cannot be judged by the usual standards. Orlansky describes the concept in this way: "The two large instruments are used jointly to represent the three-dimensional geometry of the flight situation, in each case by means of a projection relevant to the tasks accomplished during flight, that is, maneuvering in a three-dimensional space with respect jointly to altitude, azimuth and speed both for immediate (attitude) and long-term (navigation) purposes" (42)

Many displays augment numerical values by pictorial aids (the Hughes panel is an elaborate example of this), but in the contact analog numbers function merely to supplement pictures. Chapanis (13), among others, suggests some of the advantages of pictorial over symbolic displays such as the need for less initial training, greater interpretability and realism. However, this display will not be "realistic" in any accepted sense of the word, and no experiments done so far assess the value of a completely integrated "pictorial" system of any sort. Only the several periscope studies seem interesting in this context; they show that pilots can fly with no other display than an imperfect reproduction of the real world (cf 36).

The great strength of the contact analog would lie in the fact that it proposes to take over from the pilot virtually all his present integrative duties, thus leaving him free to operate with that peculiarly human attribute, judgment.

HUGHES

The concepts underlying this presentation might briefly be stated as the fixed earth coordinate reference principle and the pursuit as opposed to compensatory tracking principle, both of which are supported by a bulk of experimental evidence, some of which is quoted by Roscoe (47). The advantages of this display lie primarily in its completely consistent orientation with respect to the fixed earth coordinate system, its coherent presentation of director information, the integration of certain information, the use of pictorial aids where possible and the fact that almost every relationship displayed has been shown experimentally to be superior to its more obvious alternatives. The principle disadvantages are its unfamiliarity to the current pilot and the lack of precision which may arise from using fixed background indicators in a limited panel space. There are solutions offered, albeit imperfect, to increase the precision of certain of the indicators. Whether the demonstrated superiority of the moving pointer over the moving scale for check and qualitative readings would entirely compensate for lack of quantitive precision under actual flight conditions can only be decided by research; the expectation is that it would (cf 14, 16, 51). It is also probable that the panel would be relatively easy for new pilots to learn for, as Fitts says, "Learning should be most rapid ...... when the direction of movement, the mode of operation of controls and the principles of instrument display agree with the population sterotypes"(21).

## WADC

The underlying concept is one of a fixed aircraft reference with integration in terms of horizontal and vertical reference lines (34). Against the horizontal scan line are read changes in those parameters related to pitch; the vertical reference relates heading indications. Thus, "flight information is presented in references consistent with the control motions and actions required" (61). The major advantages of the presentation lie in the fact that the pilot will always know where to look for his instrument reading; there are fewer production problems than could arise with a more radical display; actual and director information is provided throughout in limited form in analogous manner; the moving scale versions of many of the instruments permit any degree of accuracy desired. What is gained in precision, however, may be lost in interpretability; there is little support for the earth-reference principle in the literature of instrumentation. Moving-point indicators are generally accepted as better than moving scales for all but quantitative readings (2), and it is probable that pilots can make even quantitative readings quickly and accurately from moving pointers under the dynamic and familiar conditions of flight (cf 14, 51). In the paricular case of vertical moving scales, confusion of display-control relations is unavoidable; either scale motion must be in opposition to that of the controls or the scale values must be ordered in violation of the expected relation of numbers that increase from the bottom up (cf 5).

It must be said that, despite these difficulties, the details of the display have been worked out with great care. The display of director information and pictorial aids will save the pilot considerable interpretation time, but a <u>consistent spatial orientation</u> is lacking. There may be many occasions where time is lost because the pilot will have to <u>read</u> instruments to be certain that performance is correct.

NAVY: System Function: Cruise Control

**Description**

**A. POWER:** Unspecified

In terms of percentage thrust on independent display

B. ENGINE CONDITION: Unspecified

C. FUEL CONSUMPTION:

A point of return should occur on the map as fuel supply for return to base becomes low.

D. FUTURE:

It is assumed that a series of throttle settings can be adjusted to match priorities of economy, range or time.

**Discussion**

C. FUEL CONSUMPTION

Rationale: The point of return (shown as a circle on a "barrier") encloses an area inside of which the targets or destinations may be reached and still allow a safe return to base on the basis of specific conditions existing with regard to fuel, power setting, wind, etc. At all times the contour of the line should warn and predict for the pilot what his range capabilities are.

HUGHES: System Function: Cruise Control

| Description | Discussion |
| --- | --- |
| The only specification is for FUEL CONDITION (see Navigation: C 4). | Power and fuel management assumed to be provided by airframe manufacture |

## Description

A. ENGINE INSTRUMENTS:

"The engine instrument group may be divided into subgroups according to the way that the individual parameters interrelate and the way in which the information is used."

1. Power group
2. Cruise control group
3. Fuel management group

B. POWER INSTRUMENTATION:

1. Five parameters
2. Mode Selection: five mode selection buttons index moving scales so that the desired value of each parameter is in the center of the scale window. When the engine is operating properly all pointers are aligned.

## Discussion

B. POWER INSTRUMENTATION:

Experiments have shown that with a group of instruments pointer alignment makes identification of a deviation in one much quicker and more accurate. It is generally accepted that alignment of all pointers at 9 o'clock (as they are aligned here) permits the most rapid and accurate checks (16, 57, 58).

| Description | Discussion |
|---|---|
| 3. Trend information: percent thrust, percent RPM and exhaust temperature are also presented on circular scales to show the complete range of values and thus provide indication of trends. | |
| 4. Proposed development: indexing will be automatic as function of throttle position, existing temperature and pressure, etc. | |

C. CRUISE CONTROL

1. Select either constant Mach or constant altitude cruise.

   a. Constant Mach: altitude deviation indicates best altitude to attain best range.

   b. Constant altitude: Mach deviation gives speed for best cruise.

2. Deviations: in final model deviations will not appear, but will be indicated on the Mach and altitude instruments by actuation of the command index.

WADC: System Function: Cruise Control (continued)

| Description | Discussion |
|---|---|
| 3. Optimum range: appears in counter window showing expected range if directions of Mach and altitude deviation indicators are followed out. | |
| 4. Actual range: appears in another counter window showing range with existing power, altitude and aircraft configuration. | |
| D. FUEL MANAGEMENT: | |
| 1. Present instruments have moving pointers against scales that have no graduations except into four quarters to give qualitative indication of fuel quantity.<br>a. Separate indicators for each fuel tank<br>b. One for total fuel quantity | |
| 2. Future instruments will integrate the fuel consumption display with range, endurance and time-to-go information. | |

**NAVY: System Function: Navigation**

| Description | Discussion |
|---|---|
| A. SITUATION DISPLAY: | A. SITUATION DISPLAY: |
| To a large extent navigation information is presented on the horizontal display described below; | |
| 1. Map projection | 1. The Lambert conformal projection was selected because it is used for aeronautical charts. All directions within standard parallels are approximately true; great circles are nearly straight line; figure representation is conformal to true shape. |
| 2. Shape: circular surrounded by compass rose | 2. The circular shape allows integration of compass rose and directional indications. |
| 3. Size: 10-inch diameter | 3. The ten-inch diameter subtends 20° at normal cockpit viewing distance and is thus within the limits of optimum viewing angle for normal fixation. |
| 4. Scale: a. Master; b. En route; c. Terminal | (1 - 3 are covered in reference 31). |
| 5. Map selection: must provide for maximum range of aircraft by continuously generated map or reservoir with convenient selection features. | 4. Various experiments have shown that subjects perform much more accurately and prefer a stable map or other navigational reference with a moving own aircraft symbol to a display which moves in relation to a fixed own aircraft reference (38, 43, 44, 48, 59). |
| 6. Map stable: own aircraft symbol rotates with heading changes and traverses with track made good | |

NAVY: System Function: Navigation (continued)

| Description | Discussion |
|---|---|
| B. HEADING: | |
| 1. By orientation of an aircraft symbol and index marker on compass rose | |
| 2. Numerical definition on compass rose for use in communication and in coordinating flight direction with other facilities | |
| 3. Wind drift may also be defined by the divergence of heading and track indications. | |
| 4. Read to nearest degree | |
| C. COURSE INDICATION: | |
| 1. Adjustable course line and an arrow indicator on compass rose (44) | |
| 2. Command course given by a line which responds to a computer or external commands. Pilot may adjust line with respect to map surface. Appears as straight line between points on map (44) | |
| 3. Course arrow indicator at perimeter of display gives numerical definition of true direction of course line. If a command course which is not straight is in effect, the course arrow will alter in time corresponding to the target of the command position (44). | |

NAVY: System Function: Navigation (continued)

| Description | Discussion |
|---|---|
| 4. Read to nearest degree. | |
| D. POSITION RELATIVE TO BASE: | |
| (Similar to position relative to targets, other aircraft) | |
| 1. Point of return should occur on map as fuel supply for return to base becomes low. | |
| 2. Command position: deviation of own aircraft symbol will show navigation error in space and time. | |
| 3. Track: decaying record or track of own aircraft, carriers, etc., should be available (extend one inch on display), length related to speed (not to exceed one inch). | |
| 4. ETA: appears in counted box at top of display | |
| 5. Speed: (See also Flight Control). Ground speed is required in order to navigate according to a time schedule. The pictorial display of track distance, own aircraft symbol, command position, as well as an automatically calculated ETA gives best speed and makes quantitative definition of ground speed unnecessary. | |

HUGHES: System Function: Navigation

Description

A. SITUATION DISPLAY (Incomplete):

Navigation information is presented on the horizontal-situation indicator, described below:

1. Map of an area about a selected TACAN station or other navigational reference

2. Shape: circular surrounded by compass rose

3. Scale: X, Y, Z, miles in diameter

4. Map stable: own aircraft symbol rotates with heading changes and traverses with track made good.

B. COURSE AND HEADING:

Manual selection of mode, either

a. Manually selected course
b. Automatic command heading
c. An ADF bearing

(This selection linked to heading and command repeater, see Flight Control).

d. Own heading given by arrow read against compass rose

Discussion

GENERAL:

The similarity of this display to the Navy Horizontal Display is apparent. The same remarks apply.

HUGHES: System Function Navigation (continued)

| Description | Discussion |
| --- | --- |
| C, <u>POSITION RELATIVE TO BASE:</u> | C. <u>POSITION RELATIVE TO BASE:</u> |
| (Similar to position relative to targets, other aircraft) | |
| 1. Own position and heading shown | <u>Two Schedules</u> |
| 2. Command position and heading given | 1. Maximum range |
| 3. Target(s) displayed where appropriate | 2. Minimum time |
| 4. Shrinking circle, concentric with own aircraft indicates distance pilot can expect to fly with fuel remaining. | Computed by central computer with solution indicated in command speed and altitude. Indicates what aircraft can do with remaining fuel. Circle of varying diameter contracts about aircraft symbol on horizontal map display, diameter indicates maximum range. |

WADC: System Function: Navigation

## Description

**A. SITUATION DISPLAY:**

Developments are in progress for a situation or map display. One of these is an optical system, another is a TV system. There are resolution advantages of the optical system and in addition the presence of color, which is lacking in the other.

The Display:

1. X-inch display
2. Aircraft symbol can be slewed to center.
3. X-mile slew, X error; latitude and longitude of correct position
4. Map will rotate
5. Slide for map on standard spectroscopic plate
6. Black and white; high resolution obtained by placing color emulsion over black and white.
7. Map slide can be removed in air by pilot. Coordinate corrector (or secant corrector) xy to latitude-longitude.
8. Counter for present position latitude-longitude

## Discussion

**A. SITUATION DISPLAY:**

Like all other instruments, the situation or map display will be earth-referenced. Experiments have shown that subjects do not perform so well with this type of display as with one in which one's own aircraft symbol moves in relation to a stable map. (See Navy, Navigation, A 4).

| Description | Discussion |
|---|---|
| 9. Possible to supply other information on tube, i.e., check-off lists, fuel consumption, SAGE and TACAN (at present the system is self-contained). | |
| B. THE TRIANGULATION PROBLEM: It is felt necessary to display this to the pilot even if a map-type display is available. | B. THE TRIANGULATION PROBLEM: With cockpit space at a premium, it is important that unnecessary instruments be left out. Whether or not this display is needed should be decided by experiment. |
| The Display: | |
| 1. The output of any navigational equipment such as ILAS, AGCA-VOLSCAN, TACAN, VOR or GCI may be selected for primary presentation. | |
| 2. A rotating card heading presentation bearing pointer and vertical needle have been combined to show pilot own heading and position relative to desired navigation or interception course. | |
| 3. Actual heading: read from etched line against a rotating compass rose. | |
| 4. Command heading: given by a split T symbol which may be remotely positioned or set by pilot as a memory reference. | |
| 5. Course displacement needle: angular position is oriented with desired course to destination. | |
| 6. Outer periphery marker indicates direction to known fix, operated by mode selection. | |

## NAVY: System Functions: Search and Detection, Tactics, Attack

| Description | Discussion |
|---|---|
| A. SEARCH AND DETECTION:<br><br>An integrated insertion on vertical display<br><br>B. TACTICS:<br><br>1. Target Information<br>a. Position angle<br>b. Azimuth<br>c. Range<br>d. Range rate<br><br>2. Vertical Display: Coding<br><br>a. Lead Pursuit<br>Inverted T<br><br>b. Lead Collision<br>Same inverted T<br>Error circle is fixed at display indication of Y-Z axis of aircraft.<br><br>c. Pursuit: compatibility with visual sighting (compressed vs. real space, head vs tail discrimination). Use of horizontal display for guidance? Problem should be solved by experimentation.<br><br>d. Firing Point<br>(1) Verbal count-down 10-1 "Fire" for pursuit | A., B. AND C. SEARCH AND DETECTION, TACTICS, ATTACK<br><br>The description of the displays is so far incomplete. Few experimental results apply directly to the proposal though human engineering considerations have been taken into account (e.g., 15).<br><br>The choice of a verbal count-down for pursuit firing should be better than a visual order which would clutter the integrated display and would not be responded to any more quickly (10). |

| Description | Discussion |
|---|---|
| (2) Automatic for collision | |
| e. Breakaway Point | |
| (1) Flicker of error circle | |
| (2) Use of a symbol already on the display to give a go-no-go command | |
| (Go-no-go commands may be given symbolically in some way consistent with other such commands by a signal not an integral part of the contact analog. Such commands have no spatial character and are univocal, and this arrangement preserves the simplicity of the CA and immediacy of interpretation). | |
| 3. Horizontal Display: Coding | |
| a. Identification | |
| (1) Enemy objects coded | |
| (2) Friendly objects not coded | |
| b. Target Assignment | |
| (1) The target is the circled enemy object. | |
| (2) It will be letter-coded for tactical procedure. | |
| c. Altitude | |
| Should be conveyed numerically next to aircraft and obstacle symbols when such information is available. | |

| Description | Discussion |
|---|---|
| C. ATTACK: | |
| 1. Air Target Symbols<br>Three symbols capable of separate or simultaneous display. The size of each symbol, when displayed, shall vary as a function of the range of the real target it represents. | |
| 2. Ground Target Symbol<br>A bull's eye symbol to lie in the ground plane at target position | |
| 3. Firing Point Symbol<br>A two-dimensional representation oriented in a plane normal to the displayed flight path. It is possible, in the case of a rapidly maneuvering air target, that the firing point symbol will not be anchored to the flight path ribbon. | |

HUGHES: System Functions: Search and Detection, Tactics, Attack

## Description

A. MA-1 SYSTEM:

This is a complete system for the aircraft and has implications in all three system functions.

1. Search and Detection

   a. Radar subsystem will perform automatic searching, automatic tracking, ground-map and beacon operation.

   b. IFF system automatically replies to interrogation from ground stations and aircraft and will permit interrogation of other aircraft.

   c. Radar under control of the pilot scans region in front of the interceptor.

2. Tactics

   a. This is the integrated electronic and control system.

   b. It will constitute all of the electronic equipment required in the interceptors from takeoff to touchdown.

   c. Provides for missile lead-collision attacks and for rocket lead-collision and lead-pursuit attacks.

   d. Towards the end of the approach course, the pilot reviews the tactical situation and selects the armament to be fired.

## Discussion

A. MA-1 SYSTEM:

A fuller discussion of the Hughes Fire Control systems appears in reference 13, and description of MA-1 by Hughes. Human engineering recommendations (cf 15) and research have been taken into consideration. Experiments have been done to determine the best manual steering display (41, 49).

Flight director task is similar except for attack steering. Hughes requires moving aircraft, WADC moving horizon and error dot during attack phase.

NAVY: System Function: **Flight** Control

## Description

A. GENERAL: Description of vertical display

1. Horizontal planes displayed:

   a. Ground (patterned)
   b. Horizontal barometic
   c. Minimum safe altitude

2. Flight Path Datum Plane

   a. Composed of single axis random circles

   b. Appears as "transparent" ribbon of varying widths

3. Impact Point

   a. Expansion point of display in motion
   b. Gives sensitive indication of flight path deviation from program

## Discussion

A. GENERAL:

1. Horizontal planes covered under Attitude and Altitude below

2. Flight Path Datum Plane

   The ability to fly as directed by the flight path datum plane will determine how well the pilot will maintain the following:

   a. Climb: safe and proper rate
   b. Let down: safe and proper rate
   c. Best altitude
   d. Command headings (to some extent)
   e. Speed (to some extent)

   A simulator study showed that beam tracking on a contact analog display with the flight path superimposed over a dot or grid pattern was extremely easy and accurate, more so than with a conventional gyro and compass (32). Texture gradient will always be discriminable to pilot.

3. Impact Point

   a. There is sufficient evidence to say how sensitively the impact point can be used as an indication of deviations from the flight path program.

   b. One study shows estimates to be fairly accurate over a range of expansion

| Description | Discussion |
|---|---|
| | velocities and vertical positions of the impact point but the estimates seem to depend on velocity (varibility higher at low expansion velocities) and texture (variability higher with coarse textures) (18). |
| | c. A simulator study with a complex pictorial landing display produced extremely accurate estimations of the touchdown point at simulated landing speeds (30). |
| B. ATTITUDE: | B. ATTITUDE: |
| 1. Roll indicated by motion of all horizontal planes | 1. Planes obey the rules of deformation of the image for the observer in motion (27) |
| 2. Pitch and roll (slant) indicated by texture perspective of patterned ground and flight path datum planes. Ground reference plane texture structure composed of randomly organized elements of various sizes and shapes. | 2. Experiments show that accurate estimates of slant can be made when the perspective transformations are seen to occur (28). |
| | 3. Under the conditions (2) both a grid and random dot pattern resulted in quite accurate estimates of moderate degrees of slant. |
| C. ALTITUDE | C. ALTITUDE: SEE A-2. |
| 1. Ground plane datum and slatted fence | |
| 2. Minimum safe altitude plane, coded | |
| 3. Best altitude and | |
| 4. Let down (safe and proper rate) given | |

**Description**

by flight path datum plane and impact point

D. CLIMB:

Safe and proper rate given by flight path datum plane and impact point.

E. HEADING:

1. Some heading information in director form is implicit in flight path datum plane.

2. Horizon line calibrated (Lubber line = $C_L$ of airplane) providing numerical information in same frame of reference as spatial display.

F. SPEED:

1. Normal quantitative indications not contemplated

2. Consideration of excess or insufficient speed built into Vg indications and flight path programming.

3. Best speed, non-quantitative velocity track, see Navigation.

4. Vg: green, yellow, red lights or stick shakes
Go-no-go commands may be given symbolically in some consistent way by a signal not an integral part of CA since such

**Discussion**

D. CLIMB See A-2

E. HEADING: See A-2

F. SPEED:

See A-2 and Navigation display.
Vg. implications for under Warning

The movement of the texture elements of the ribbon across the visual field shall be a function of ground velocity and distance of observer from ribbon. Adjacent to and on the left side of the flight path ribbon there shall be a narrow track (velocity track) whose texture elements are different from those of the ribbon and whose motion across the visual field will be a function of the difference between actual ground speed and programmed ground speed. When actual flight velocity is equal to

NAVY: System Function: Flight Control (continued)

| Description | Discussion |
| --- | --- |
| commands have no spatial characteristics and are univocal. | the programmed flight velocity the texture elements of the velocity track shall remain stationary in the display. Slower or faster with respect to programmed flight, velocity track shall appear to move away from or toward. |

HUGHES: System Function: Flight Control

| Description | Discussion |
|---|---|
| **A. GENERAL:** | **A. GENERAL:** |
| 1. All instruments conform to the aircraft reference principle. | 1. The superiority of this mode of reference has been demonstrated under many conditions (see below B-1; Navigation: Navy, A). |
| 2. All scalar displays are of the moving-pointer type. | 2. Scalar Displays<br>a. Moving-pointer indicators are generally superior to the moving-scale variety. They can be checked and read qualitatively more quickly and accurately (16, 51, 56); and although they cannot be read so well quantitatively under some conditions (cf 15), when the situation approximates that of actual flight and user expectancies where to look can be utilized, there is no real advantage to the moving scale (14, 51, 60).<br>b. Better display-control compatibility is inherent in the moving-pointer indicator which should produce faster and more accurate responses (cf 5, 22 23). |
| 3. Actual and command indications appear on all displays using identical or consistent own aircraft and "follow-me" steering symbols.<br>A consistent target symbol also appears where appropriate. | c. The display of both own aircraft and steering symbols makes the obedience to commands a pursuit tracking task, the generally superior mode of tracking (cf 4, 11, 12, 50). |

HUGHES: System Function: Flight Control (continued)

| Description | Discussion |
| --- | --- |
| **B. ATTITUDE - DIRECTOR:** | **B. ATTITUDE - DIRECTOR** |
| 1. Centrally located, shows aircraft attitude at all times and steering commands in ILS-director mode and the manually selected heading mode. | 1. The moving aircraft configuration for attitude indication has been shown superior to the moving horizon under a wide variety of experimental conditions using naive subjects and unpracticed pilots (8, 9, 25, 26, 37, 45). |
| 2. Vertical Position<br>a. Aircraft symbol indicates true vertical flight path angle.<br>b. Steering commands by vertical displacement of diamond-shaped index | 2. Current pilots use the familiar moving horizon as well or somewhat better than the moving aircraft. However, even they make many reversal errors with the conventional instrument (7% in one case) and the majority express a preference for the other display (9, 20, 24, 25). |
| 3. Horizontal Position<br>a. Rotation of aircraft symbol gives bank against fixed horizon reference.<br>b. Lateral displacement of aircraft symbol indicates horizontal steering error. | 3. Pilots like a combination of heading and attitude, but there is a suggestion that combining the indications reduces the efficiency with which the display can be used (1, 19, 20). |
| **C. HEADING:** | **C. HEADING:** |
| 1. Placed upper center above attitude display<br>2. Shows heading against an automatically settable card, top center of which indicates: | Selection of various heading indications means pilots make the same right-left discrimination under all conditions. Two experiments found a moving pointer in the upper half of a compass-type dial produced more accurate responses than a variety of other displays (35, 39). |

| Description | Discussion |
|---|---|
| a. Manually selected heading<br>b. Automatic command heading, or<br>c. ADF bearing | |
| **D. ALTITUDE:** | **D. ALTITUDE:** |
| 1. Alternative vertical scales with moving pointers<br>a. Expanded scale from X to Y feet.<br>b. Z to A feet.<br>c. Drum type indicator interpolates within B-feet intervals. | 1. Vertical scales were read more quickly and accurately than the conventional 3-pointer altimeter (29).<br>2. Vertical altitude indicators of this type (undistorted spatial analogs) showing predicted altitude, an integration of vertical speed, and command altitude produced quicker and more accurate flight decisions than various dial-type and a counter display (52, 53). |
| 2. Displayed<br>a. Present altitude<br>b. Command altitude | The presentation of predicted altitude based on a few second of vertical speed looks to be a very good feature.<br>3. The counter-pointer for interpolation is a bad feature (though it may not be used very often), but is forced on the design in interest of precision. It will decrease the speed and accuracy with which quantitative readings can be made (2,29).<br>4. Pilots like clear low altitude warning (7). |
| **E. RATE OF CLIMB:** | **E. RATE OF CLIMB:** |
| A moving pointer presentation of rate of climb | See A-2. |

HUGHES: System Function: Flight Control (continued)

| Description | Discussion |
|---|---|
| **F. SPEED:** | **F. SPEED** |
| 1. Lower Half of Display | See A-2. |
| a. Indicated airspeed<br>b. Standard speed based on angle of attack mapped into a stall region at bottom<br>c. Zone bracketing the point of maximum lift/drag ratio for approach and climb out | |
| 2. Upper Half | |
| a. Mach number<br>b. Command Mach<br>c. Maximum safe speed corrected into Mach number | |

WADC: System Function: **Flight Control**

| Description | Discussion |
|---|---|
| A. GENERAL: | A. GENERAL: |
| 1. All instruments conform to the earth-reference principle, and | 1. Earth-referenced displays have been shown to be generally inferior to the aircraft reference type (see Hughes A-1). |
| 2. All scalar displays are of the moving scale variety except two, the rate-of-climb indicator and altitude-planning scale. | 2. Moving-scale indicators are generally inferior to the moving-pointer type (see Hughes A-2 a). Their main advantage is that any degree of precision can be incorporated into the display (see Hughes D-3). |
| 3. Present and command information is provided throughout and all readings are made with reference to a horizontal scan line. | 3. The horizontal reference line may lead to quicker and more accurate quantitative readings, but the fact that some scales read up and others down may result in interpolation errors. |
| | 4. Despite the fact that all factors and parameters related to pitch are read along this scan line, there is poor display control compatibility (cf 5) and the obedience to commands involves compensatory tracking behavior which is generally not so good as pursuit (see Hughes A-2 c). |
| B. ATTITUDE-DIRECTOR | B. ATTITUDE-DIRECTOR: |
| 1. Two possible displays are suggested (I and II below) differing in the display of command pitch steering guidance. Both are basically moving-horizon displays. | 1. The moving-horizon display will be familiar to current pilots, but there is much to suggest that the moving aircraft is the more "natural" display and thus would be learned more quickly by pilots in training (see Hughes B). |
| a. Display I<br>(1) Roll<br>(a) Actual: by motion of horizon | 2. The choice between displays I and II can |

| Discription | Discussion |
| --- | --- |
| line in opposition to the direction of roll | only be made by experiment or expediency. |
| (b) Command: vertical line superimposed over display and displaced in direction of command roll. Disappears from sight when not in use | |
| (2) Pitch | |
| (a) Actual: by motion of horizon in opposition to changes in pitch | |
| Command: horizontal line superimposed over display moves in direction of command pitch. Disappears when not in use | |
| (b) Display II | |
| (1) Roll: identical to display I | |
| (2) Pitch: In some modes of operation the aircraft sumbol is permitted limited movement in the direction of pitch changes and opposite to sphere. This allows detection of very slight pitch changes and is scaled to relate directly to Pitch Error Indicator at the left of the aircraft symbol (see below) so that when the two are matched the aircraft is guided smoothly into the desired path and held there. | |

2. **Pitch Error Indication:**

Shows displacement information in a con-

| Description | Discussion |
|---|---|
| ventional manner from:<br><br>a. Glide slope<br>b. Desired altitude<br>c. Computed altitude<br>d. Other desired condition<br><br>Note: Where an asterisk (*) appears the instrument has both Phase I and Phase II designs. Phase I instruments were experimental only, Phase II are intended for development if tests are successful; only Phase II designs are described. | |
| C. ALTITUDE AND RATE OF CLIMB:<br><br>These indications are presented side by side sharing a common reference. The relation between rate of climb and altitude changes can be accomplished smoothly by the appropriate changes of the rate of climb index.<br><br>1. Rate-of-Climb Indicator<br><br>a. Moving-pointer indicator scaled for ±2000 feet per minute.<br>b. Beyond ±2000 a moving scale is actuated to show a number appropriate to the higher rate.<br><br>2. Altitude<br><br>a. Actual Altitude: A moving scale (increasing upwards) is read opposite the zero of the rate-of climb indicator.<br><br>b. Command Altitude: Appears on scale and in counter-bank below<br><br>c. Planning Scale: A vertical spatial | C. ALTITUDE AND RATE OF CLIMB:<br><br>(Presumable the scales for the rate of climb and altitude indicators are so chosen that when the command altitude on the moving scale and the rate-of-climb pointer come into coincidence they can be guided together back to the zero reference. If so, despite the use of two types of scale and the reading problem this might produce, this particular presentation should be fairly easy to use. The addition of the Planning Scale (not included in the Phase I display) supplies instantaneous information about the aircraft's vertical position in relation to other positions on the spatial analog). |

| Description | Discussion |
|---|---|
| analog incorporating coded symbols for the following:<br>(1) Actual altitude<br>(2) Command altitude<br>(3) Target altitude (also appears in counter-bank)<br>(4) Cabin pressure (added to this scale to eliminate redundant indicators) | |
| 3. Counters: Three appear at bottom of display giving:<br>a. Command altitude<br>b. Target altitude<br>c. Barometric pressure | |
| D. MACH, AIRSPEED AND ANGLE OF ATTACK:*<br>These three indicators appear side by side and are read along a common horizontal reference.<br>1. Mach and Airspeed<br>a. Decreasing values of Mach and airspeed appear at the top of the tapes to provide consistent presentation of command information and indications consistent with pitch changes, i.e., increase in pitch results in decrease of Mach and airspeed.<br>b. Command indices are positioned from the output of airborne computers operated through data link and manually set by pilot. | D. MACH, AIRSPEED AND ANGLE OF ATTACK:*<br>The common reference makes clear the relation between the three elements, but the general arguments against moving scales (see Hughes A-2) apply. There is a further opportunity for confusion here since the tapes increase in a direction opposite to that of the altitude scale and to normal expectations. |

WADC: System Function: Flight Control (continued)

| Description | Discussion |
|---|---|
| c. Below Mach 0.5 the tape has pictures showing if it is safe to lower gear, flaps or open drag chute. | |
| 2. <u>Angle of Attack</u>: Moving tape with the following indications: | |
| a. Light colored region around zero marking indicates normal cruise angle of attack. | |
| b. Dark region above center reference indicates desired angle of attack for approach and landing. | |
| c. Cross hatching moves towards center reference when approaching stall. | |
| d. White reverse L-shaped area is indication of G. | |
| (Thus the clear area above the center reference gives the margin of maneuver. Whether G or angle of attack means the same to pilot in terms of the control action needed.) | |

NAVY: System Function: Communication

| Description | Discussion |
|---|---|
| **A. RIGHT CONSOLE:** | |
| 1. Master Radio Control Switch | |
| 2. Marker Beacon Switch | |
| 3. Navigation Receiver | |
| 4. UHF | |
| 5. Select Control Radio | |
| 6. Radio Compass | |
| **B. SWITCHES FOR:** | |
| 1. Inter-communication | |
| 2. Marker | |
| 3. ADF | |
| 4. VHF Nav | |
| **C. CUT or WAVEOFF:** | |
| 1. Indication on vertical display | |
| 2. Pattern to fly at this command on Horizontal display (on vertical display in director form) | |

## WADC: System Function: Communication

| Description | Discussion |
| --- | --- |

**A. COMMUNICATION FUNCTIONS:**

1. Short Distance
2. Long Distance
3. Data Link
4. BROFICON
5. Navigation Aids
6. Landing Aid - Auto. ILS
7. UHF ADF (homing device)
8. IFF - air-to-air interrogator and transponder (integrate with fire control) automatic ground transponder

**B. FUTURE:**

1. At present consideration is being given to some form of integration of Communication Controls, i.e., remote channel indication and touch tuning, UHF voice at present.
2. WADC Laboratory is working to extend. Ultimate operation would be where ground makes the change and automatic mechanism in aircraft makes change.

NAVY: System Function: Housekeeping

| Description | Discussion |
|---|---|
| A. LEFT CONSOLE: | |
| 1. Flap position display | |
| 2. Wheel position display | |
| 3. Wheel control | |
| 4. Oxygen-control and indication | |
| 5. External lights controls | |
| 6. Tip tank control shut off, dump | |
| 7. Ignition normal control | |
| 8. Fuel booster pumps | |
| 9. Primer switch | |
| 10. Drag chute control | |
| B. RIGHT CONSOLE: | |
| 1. Flight instrument power switch | |
| 2. Internal lights control | |
| 3. Cabin temperature defrost | |
| 4. Cabin pressure dump (switch) | |
| 5. Auxiliary defrost (switch) | |
| 6. Cabin air (switch) | |
| 7. Trim control position indicator | |

## WADC: System Function: Housekeeping

### Description

Present thinking is in terms of master warning light and secondary lettered or word lights.

Other controls in this area will follow HIAD.

### Discussion

Just recently at least two authors have discussed the need for some sort of master warning system (6, 24). In Britain master warning systems have been in operational use, experiments having shown the superiority of an integrated system, and the fact that a visual master warning has certain advantages over an aural one (54, 55).

**FEASIBILITY**

When considering the possibility of building prototypes and/or production models of each system on a schedule useful for the Phase II program, the differences in design concepts must be kept in mind. The Navy concept of an integrated instrument system places it apart from either the Hughes or WADC concept. And, although prototype instruments are being flown in a T2V, it is doubtful that a production model could be available for the Phase I, 1959 delivery. It is possible that production models could be available for Phase II, 1961 delivery.

The WADC concept has developed prototype instruments which have been flown. Production could be expected in 16 to 18 months. At present there are some scale factor and sensitivity problems related to the proposed instruments.

Of the three concepts the Hughes system could be in production in the shortest time. Prototypes have been built and flown with reported success. Certainly this system would have no difficulty in meeting production for either Phase I or Phase II.

PHASING IN

Evaluation of the three systems in terms of problems that may be encountered in shifting from Phase I hardware to each of the systems that may be considered for Phase II, implies consideration of the similarities of Phase I and the other systems.

The Navy concept would create perhaps the greatest problems from a design point of view, as it is a different presentation from the Phase I hardware. The display generator and associated computer would have to be introduced into the Phase II system to make possible the use of the contact analog.

The Hughes system could be phased into the Phase II system with little difficulty. It requires acceptance of the moving aircraft principle and a willingness to make this transition in both aircraft orientation and fire control.

The WADC concept could be phased in as easily as the Hughes system and is slightly more acceptable as Phase I is based on the moving horizon principle. It must be pointed out that the WADC concept involves only the primary flight instrumentation and the use of this concept would necessitate compatible design in other instrument areas.

GROWTH POTENTIAL

The growth potential of each system for future weapon systems can only be estimated. The Navy system because of its unique concept would be anticipated as having the greatest growth for future weapon systems. The Hughes system, as would the WADC concept, exhibits growth potential for future weapon systems. As the Hughes system already involves more of the weapon system, i.e., flight, fire control and navigation, its growth for future weapon systems would appear assured. The WADC concept is planned for the XA and XB aircraft when built. From the point of view of expected demands on the pilot in future systems, namely "gaming" the Navy system has inherent in it the greatest growth potential.

FLEXIBILITY

The three systems require continued evaluation. At present the Hughes concept has received perhaps more formal evaluation than either the Navy or WADC concepts. The proponents of the Navy system prefer a criterion measured in terms of contact flight performance and not comparisons with existing systems. This suggests that all systems be evaluated in terms of operation requirements of actual flight. At present the only system which has accomplished this to any extent is the Hughes system. Both the Navy and WADC concepts will have to undergo a complete and thorough evaluation.

No difficulties are anticipated in evaluating any of the systems as all have sufficient flyable components to start such a study at this time.

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CONTENTS

# ILLUSTRATIONS

# INTRODUCTION

The studies carried out to determine the need for improved instrumentation for the Phase II Weapon systems were reported in Part I - the Analysis. The results of this study are summarized in Figure 27. In this plot of the most crowded moments in the mission for the pilot, the beginning of the mission from the time he is airborne at 1 minute 40 seconds to 3 minutes 40 seconds is overcrowded. Initial vectoring accuracy and/ or maximum use of the weapon system equipment must be sacrificed with the Phase I cockpit configuration. The vertical axis workload contributes heavily to this overload.

An estimate was made of the full use of the autopilot on pilot workload. This analysis assumed an autopilot which was functioning perfectly and furnished the functions of heading, Mach, attitude or altitude hold. The aircraft was taken off in the damper mode and the autopilot engaged as soon as pilot workload and safety permitted (t = 2 min 20 sec, about X feet). The pilot then used his AFCS to perform his desired initial vectoring. The complete transition from damper to full AFCS was assumed to take place in about 4 seconds, a figure obtained from the autopilot designers. During switching transitions the pilot devoted some time to making sure the mode change had successfully taken place.

Once the pilot had successfully switched autopilot modes he continued to devote a minimum amount of control time to monitoring the autopilot performance. This minimum percentage was determined from the pilot workload studies as the point the pilot was just able to exercise some control on the system. It was assumed the pilot would always spend some time in monitoring automatic performance. Figure 32 is the result of this study. Some overloading still occurs in the initial takeoff period despite maximum autopilot use.

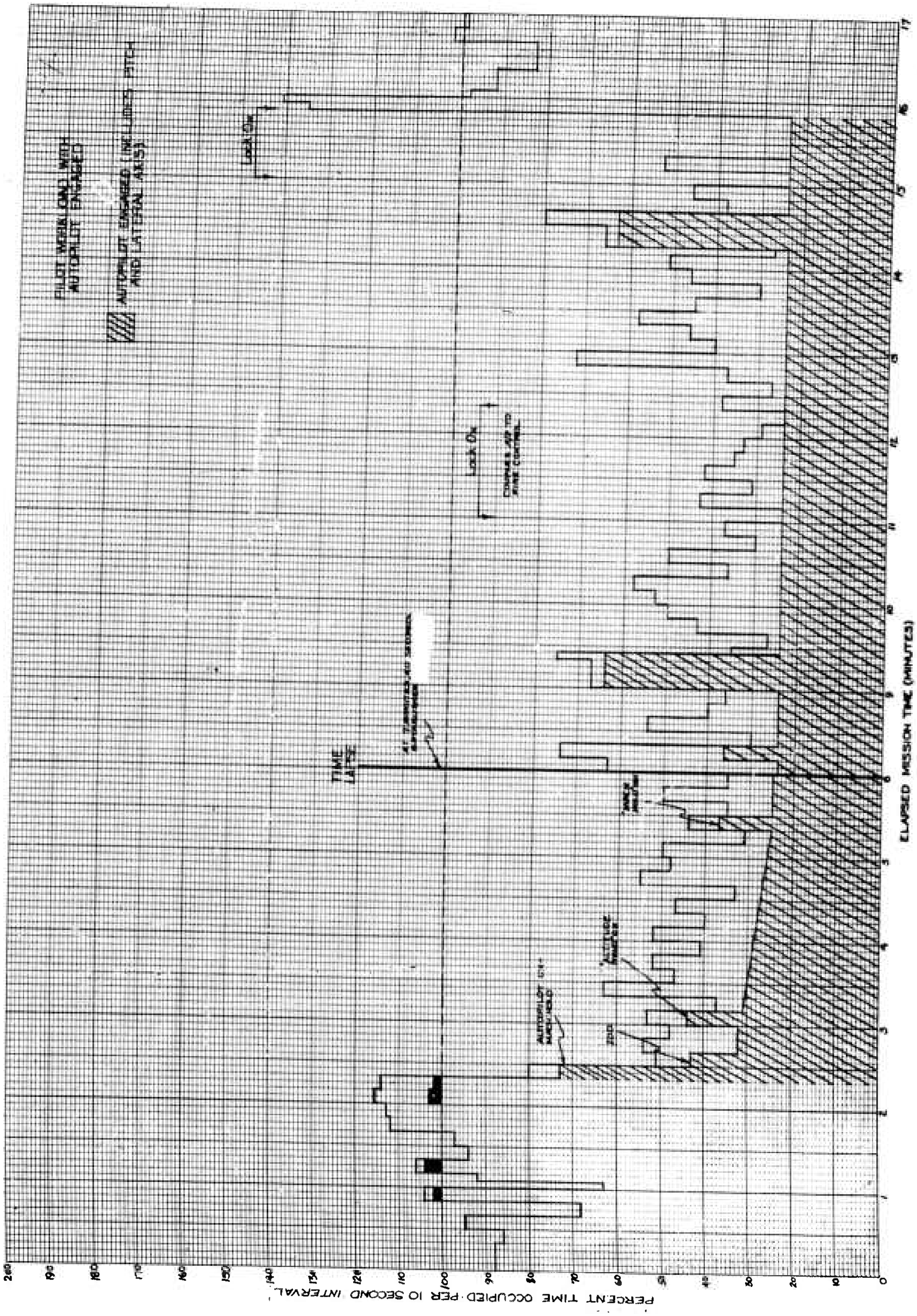



**Figure 32. Pilot Workload with Autopilot Engaged**

The analysis results suggest that a major system improvement may be obtained by improving the pilot workload situation. Improvements are suggested which considerably improve the pilot load per unit time. An analysis was made of the mission using the new system. With the exception of a slight sacrifice of control accuracy in the early part of the mission, the pilot's job was considered within the realm of human control capability. The new instrumentation development is therefore justified on the basis of the quantitative analysis. The development requires only a modification of the present Phase I cockpit.

The Honeywell study was confined by contract to the pilot's cockpit and flight control considerations of the navigator's cockpit. It is felt that a major advance in the capability of the weapon system from a human engineering standpoint is possible only by further extensive study of the rear cockpit and its relationship to the mission.

However, in the process of the mission analysis and study of the pilot's task at the points which he interacted with the man and equipment in the rear cockpit, ideas for integration of the tasks and the associated instrumentation were generated. Some of these concepts are discussed in the Appendix to this section, "A Revolutionary' Cockpit".

The study also reached the conclusion that the Navy Contact Analog, WADC Integrated Concept and Hughes Integrated cockpit developments did not offer significant increased weapon system capability for the aircraft.

The recommendations made in this report reflect the human engineering aspects of the intercept system. It is recognized that other factors make certain suggestions difficult to implement (i.e. - moving aircraft attitude indicator, etc). The objectives of this study, however, have been to recommend systems related to the human operators based on weapon system performance. It is felt that the analysis technique utilized has sufficient power to allow evaluation of the merit of such developments.

The Appendix contains a description of a more futuristic type of instrument system. This system is not a part of the recommendation since it requires further study and specification.

# SECTION I

## FRONT COCKPIT RECOMMENDATIONS

### THE OVERALL COCKPIT LAYOUT

Figure 33 is a picture of the recommended cockpit layout based upon evidence obtained in the analysis. The Phase I cockpit was found faulty in some respects by the link studies. These have been corrected in the recommendation. Pilot workload is reduced by introducing new vertical situation and engine indicators. These will be discussed in more detail later. The new configuration also allows the inclusion of the status information on the front panel and a better arrangement of console controls.

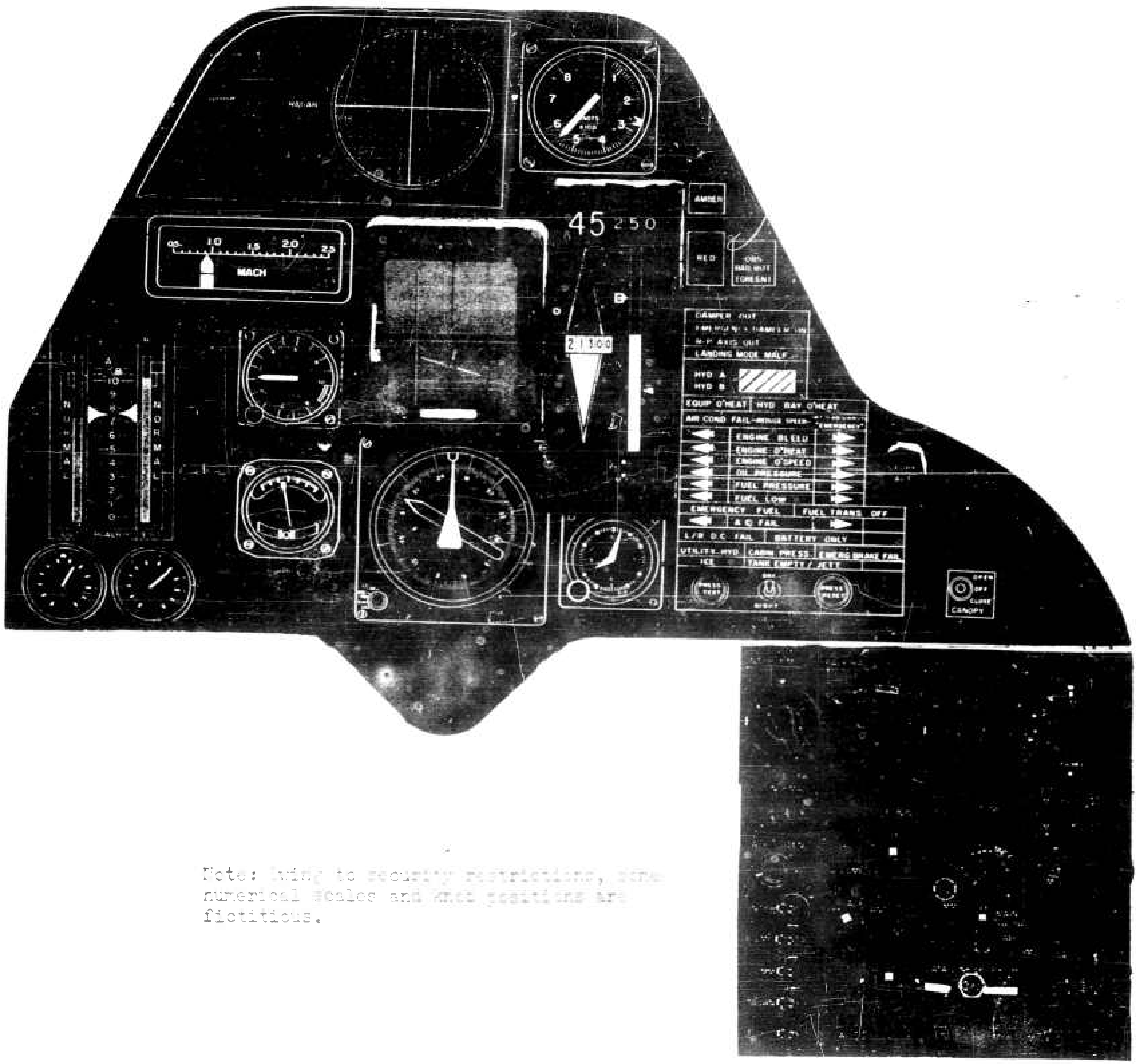
Reanalysis of the pilot workload, correcting for the new instruments, shows a considerable reduction in the workload (See Figure 34). The mean reduction in pilot workload is almost 10 percent for the overloaded minutes included in the study. The workload is brought to a reasonable level within the capability of the pilot.

The following is a discussion of the major points of departure of the Phase II cockpit recommendation and the rationale supporting each point:

1. By integrating vertical speed, altitude and command into one instrument as shown in Figure 33, perceptual transition times between the instruments is eliminated. Three separate information sources have been replaced by one scale which locates the information in one place and which integrates the information into directly usable, analog form. The check and precise reading of altitude and rate of climb have been made easier and more accurate. Planning activity has been simplified with experimental evidence pointing to a 50 percent saving in time. An informational analysis of the planning task suggests even greater savings due to the information simplification by the analog picture.

The vertical situation display is based on studies of vertical situation information, informational analysis of the problem and the experiments conducted in connection with this study (reported in Part I - Analysis). The Planning scale was expanded over that used in the Honeywell instrument experiment since it was found to be too compressed for discriminations of less than 1000 feet in accuracy.

2. The engine display has its main link with the Mach meter and has been relocated to minimize the distance between the two. This also locates it close to the throttles, which are, in effect, the power controls of the aircraft and have a logical relationship with the power display. In the event of any malfunction in the engines which will be shown in the energy display, the associated corrective control is there.




Note: Owing to security restrictions, some numerical scales and knob positions are fictitious.

Figure 33 Cockpit Recommendations

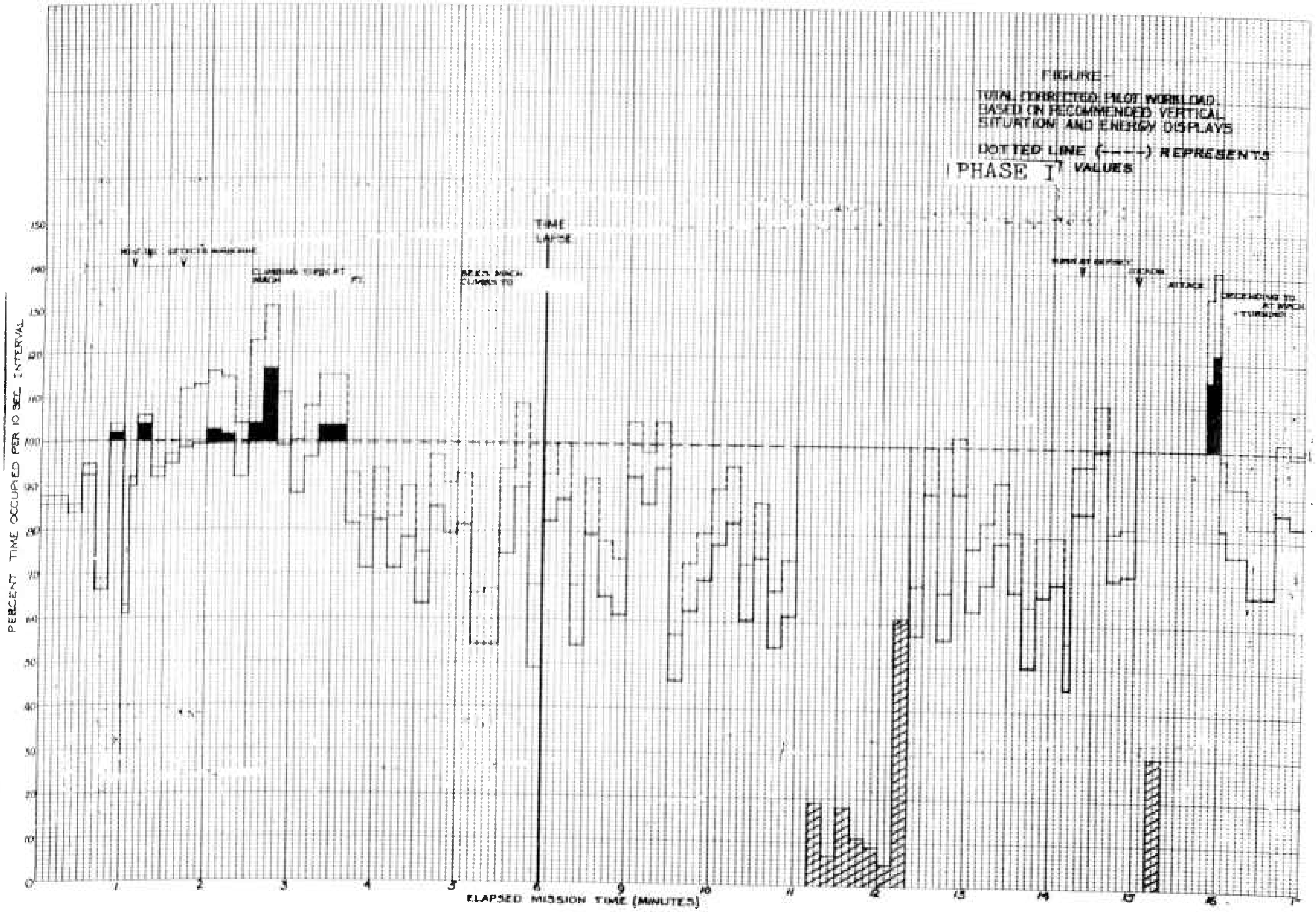



Figure 34. Corrected Pilot Workload

An easily recognizable pattern which will be established in the pilot's mind is provided by matching and integrating the power output of the two engines. In the event of malfunction of one engine, the loss of power is likely to be quickly detected by the obvious difference between the two integrated power readings; i.e., the normal engine will serve as a standard of comparison for the malfunctioning engine.

Similarly, an over-temperature condition in one engine will be readily noted by comparison with the healthy engine as well as by the abruptly appearing colored warning plague.

The fuel quantity gages, considered as the potential energy store, are properly located with this energy display.

3. The main use of indicated airspeed occurs during the landing and take-off modes, and for this reason it is primarily linked to the external environment. A relocation of IAS from below the pilot's radar scope to the top of the panel considerably shortens its link to the external environment which is important because of the desired rapid transition from instruments to contact during these flight modes.

4. The movement of the flight director-attitude indicator and the vertical speed indicator are directly related and analogous to the pilot's normal directional space perception.

5. The standby instruments are correctly related to the primary information sources. The clock is located on the side of the directional indicator. The turn and slip indicator is related to both the directional indicator and to the flight director-attitude indicator and is found close to both. The accelerometer, on the left of the FDAI, is logically linked to that instrument, the former being directly related to the integral of the rate of change of vertical position. These relationships will ease the transitions to the newer information displays when the pilot initially gains familiarization with the new cockpit, and they will further help in check reading in the event of unexpected information from the primary instruments.

6. The communication systems have been integrated into one consistent panel. The many radio control panels have been combined without eliminating any of the functions presently contained in the equipment. It is suggested that some study be given to further simplifying this area functionally as this mainly represents a physical regrouping.

DESCRIPTION OF INSTRUMENTS

Vertical Information Display

Figure 35 is a drawing of the integrated vertical display. The top five digits represent altitude. It provides the quickest possible and most error-free read-out of altitude of any instrument known (References 29 and 30). The vertical planning scale is seen on the right side. The white tape provides present vertical position with respect to the ground (base of the tape), desired or command altitude ( the bug to the left of the tape, labeled "C"), and predicted altitude base on present rate of change of altitude continued for the fixed time period of one minute. At the base of the planning scale a barometric pressure set knob is

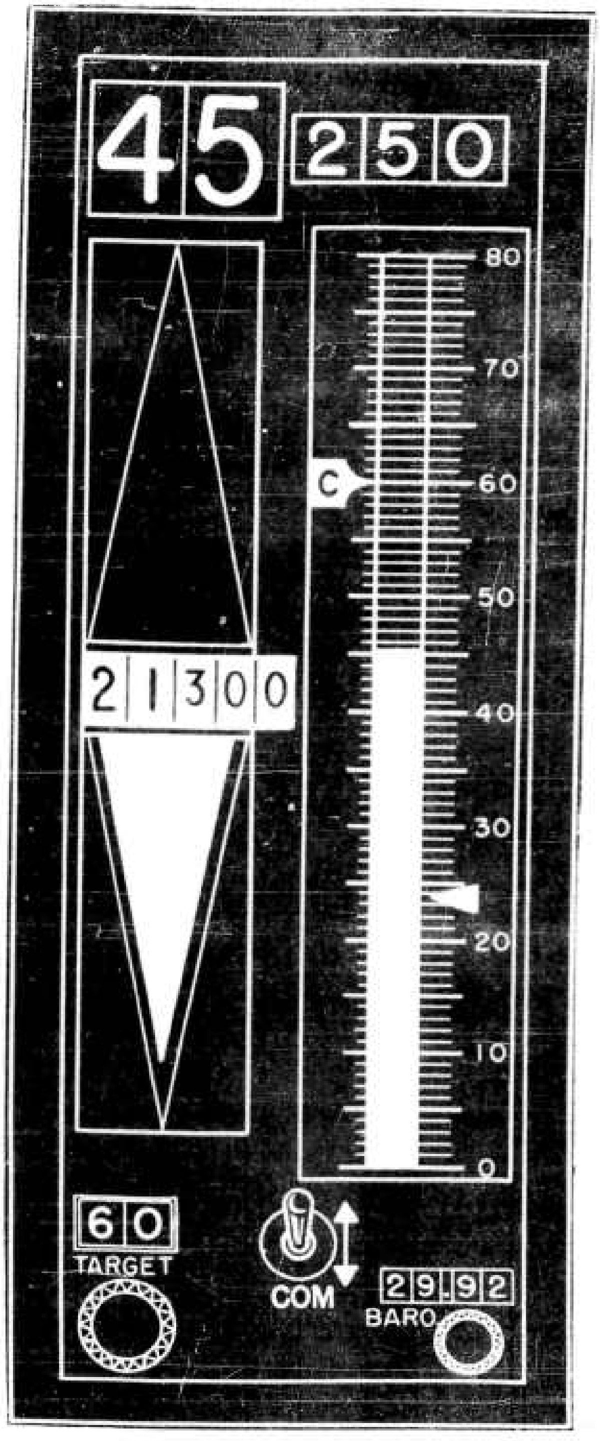



Figure 35. Vertical Situation Indicator

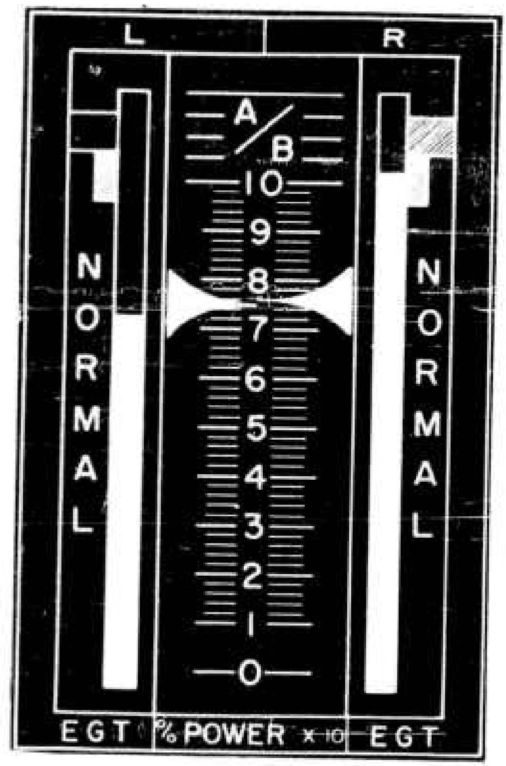



Figure 36. Engine Indicator

provided with a readout counter. On the "command side" of the planning scale a command altitude set knob is placed to enable the pilot to insert the command altitude when received verbally under broadcast control mode. Data link, when available, would provide an automatic input to position the command bug. To the lower left a target altitude set control with a two-digit counter is provided.

The vertical speed indicator on the left provides a qualitative indication of direction of change of vertical position by means of a moving tape which displays a triangle, the apex of which points in the direction of change of altitude, and the size of which is proportional to the rate of change of altitude. The five-digit number in the center (a four-place counter with a fixed zero on the right) provides quantitative rate of ascent or descent.

The direction-indicating triangle can be read using only peripheral vision so that it need never be looked at directly, either when reading the quantitative rate of change of altitude or when looking at the planning scale on the right.

Dynamically, the operation of this display would present the kind of vertical information the pilot needs at any moment in readily usable form. If a discrete look is taken to readout actual altitiude, the digital readout will take negligible time (about 0.15 second) with no error, as compared to the counter pointer altimeter (Phase I) which showed an interpretation time of 1.7 seconds and 0.7 percent errors of 1000 feet or more when experienced pilots were reading the instrument (Reference 29).

If the instrument is scanned, the pilot can quickly see his position relative to command altitude and where he will be in one minute at his present rate of ascent (or descent) without performing any of the mental integrations which would be necessary with conventional instruments to get the same information.

In carrying out a planned change of altitude, say 10,000 feet to 20,000 feet, the pilot might increase his rate of climb until he observed the "predictor" bug (right side of scale) to be at the desired altitude. Then by gradually reducing his rate of climb, as he is climbing, he can keep the predictor bug at the desired altitude. In this manner he will arrive at 20,000 feet in level flight with no overshoot. This is one of various ways in which the instrument can provide some tactical flexibility by providing "future" information, i.e., what will be, based on some present changing factor.

The design of the vertical speed indicator inherently offers any sensitivity which is available from the sensors and desirable for the control problem and it is not limited in range of vertical speed as is the conventional indicator. It provides an "up-down" pattern which is completely familiar to the pilot and, throughout its range it remains consistent in its directions. A 2-inch diameter standby counter pointer altimeter is provided to the right of the vertical situation display.

## Engine Instrument

Figure 36 is a recommended engine instrument based on display studies conducted at Honeywell. A laboratory experiment was conducted which included three aspects of system operation: i.e.:

1. Maintaining Mach command with thrust changes

2. maintaining thrust balance between engines

3. avoiding overtemperature conditions

The operator was instructed to maintain his Mach number at the command Mach unless the engine would be damaged by overtemperature and to maintain a balanced thrust condition if this did not conflict with engine temperature and/or Mach command. In a sequential or related order experiment the dial designed on the same basis as that in Figure 6 had a mean reading time of 1.43 seconds as compared to 1.95 seconds for the second best integrated instrument. Further analysis of the informational aspects of the problem indicated that the simplicity of relating the engine thrusts was the principle cause of the improvement.

A second study, unpublished to date, revealed that the danger warning qualities of the engine condition plague (EGT) were not diminished by separations such as found in Figure 36. The EGT scales are nonlinear presentations of temperature which have most of the scale devoted to the important ranges of temperature experienced in normal flight. The left engine EGT is shown in the normal range. As temperatures increase the moving tape indicator rises and as it veers or is at a dangerous temperature, a warning area becomes visible as in the right hand EGT display as shown in Figure 36. This is part of the tape which is normally invisible until the tape reaches the warning window. The tape movement is characterized so that the maximum allowable temperature is at 100 percent on the power scale. Figure 37 is an example of the way the scheme would work on an engine which has a maximum temperature of 750 degrees, limited operation at 725 degrees, and normal operation at 650 degrees.

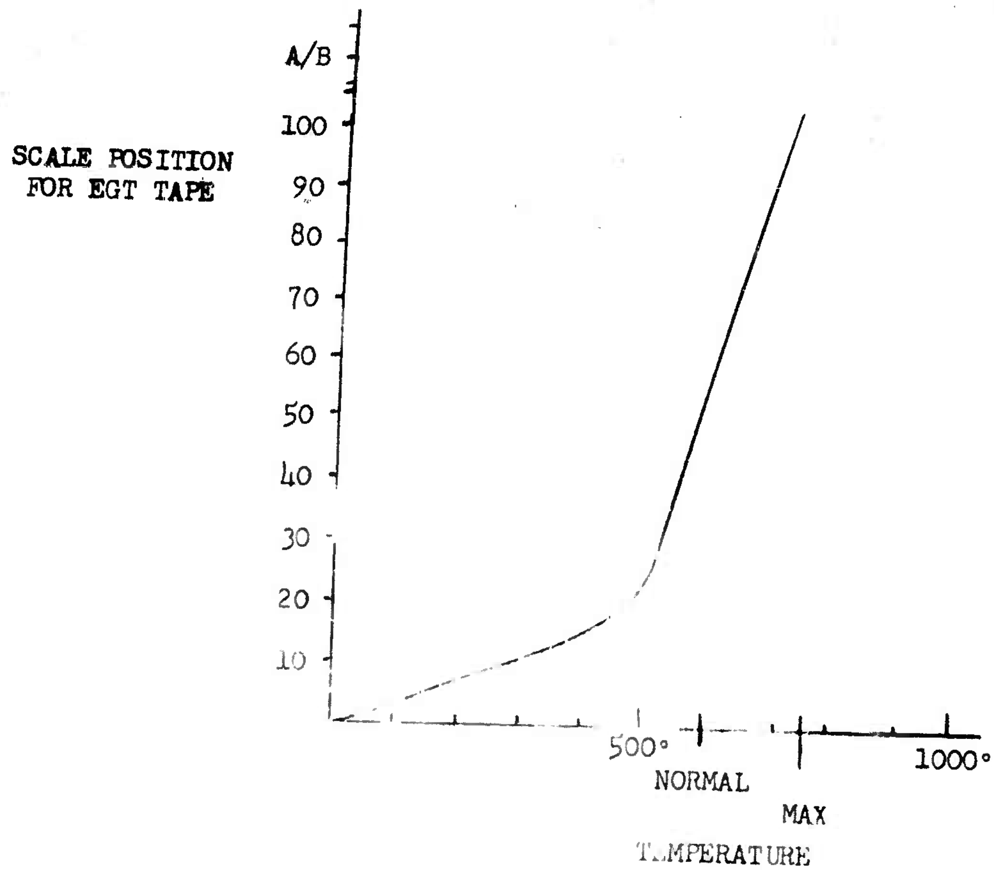



Figure 37. Characterization of EGT Scale

This allows the linear scale to have sufficient sensitivity in the region where precise temperature requirements are required while retaining an overall picture at all times.

The instrument is further relocated from the Phase I recommendation to a more desirable location as shown by the analysis. The effect of using a less desirable engine indicator is discussed in Part I - Analysis section of this report.

Speed Indication

The rationale behind the Phase I recommendation remains intact for the recommended Phase II cockpit. A linear-servoed Mach meter and a pressure-driven, indicated-airspeed indicator are shown in Figure 33. The IAS meter has been moved to make it more closely associated with its principle use frequency link which is with the outside environment. It is generally believed that stall information would be necessary for the aircraft so that a further simplification of the instrument is possible over that in the Phase I recommendation (Reference 4) by eliminating the stall warning. The function served by the stall indication in landing is provided in the visual landing aid instrument which is described later in this report.

A study of speed indication of high performance A/C leads to the conclusion that the Mach and indicated airspeed meters provide different functions for the pilot. Since the indicated airspeed is a measure of the same parameters as describe lift, this instrument is a description to the pilot of the control characteristics of his plane. It is a prime low-speed instrument. In the high speed and high altitude range it becomes an instrument which lacks the essential characteristics of

relation to the speed of sound. At speeds near or beyond the speed of sound the indication of Mach number is a more pertinent instrument. Most engineering or physical characteristics of high-speed flight are related most properly to Mach number. Buffeting, skin heating and flight control changes in the region of Mach 1, are most easily described in terms of Mach number. In the event of an electrical failure on the plane, pneumatic information supplied by an indicated airspeed meter is invaluable and can be used to direct the plane to safe emergency landing.

This desirable feature of the indicated airspeed meter, that is, its inherent correlation with the control characteristics of his plane, its operation without electricity and its good accuracy at low airspeeds tend to justify the use of indicated airspeed as a separate instrument for speed. It was therefore concluded for reasons of reliability and emergency operation that this instrument should be pneumatically driven.

Mach number is a necessary speed indication in the area characterized by compressible air flow. It is related to problems of the sonic barrier, skin temperature, cruise control, etc. It is primarily a high-speed instrument relating to complex conditions with computed desired and limit situations. It is therefore concluded that this instrument should be able to be servoed to varied information sources such as the air data computer and cruise control computer.

The Mach display system is designed to allow a clear relationship between actual command and limit values. The command indicator can be used in a vernier fashion to increase scale sensitivity for precise control such as is necessary for cruise control. Its physical desplacement from the actual Mach can be an amplified function of the difference between desired and actual Mach rather than command Mach itself. Human engineering experiments of the instrument have shown the superior reading characteristics of the display and its compatibility with population sterotypes.

The displays shown in Figure 33 are the result of human engineering studies and have been experimentally shown to be superior to other indication schemes. The differentiation of the two instruments allows quick identification of the display desired.

## Flight Director - Attitude Indicator

Figure 33 retains the flight director - attitude indicator recommended in Phase I. The flight tests and other research as described in the analysis report substantiate this recommendation. Contrary evidence is reported by the US Navy School of Aviation Medicine at Pensacola, Florida (Reference 33). This report has to do with flying a Summer's Flight Attitude Indicator. The evaluation of this hardware is considered trivial because of its inferior system performance and poorly designed display. Although all Honeywell effort on this problem has been stopped since the decision to abandon the moving-aircraft display, the human engineering recommendation remains unchanged.

Due to the decision to use the moving-horizon display concept, MH is developing an all-attitude moving-horizon display which will be an excellent instrument for

the Phase II cockpit. The project is monitored by the Honeywell human engineering effort and gives every indication of being an improved indicator. The lighting of the instrument appears especially well done.

It is suggested that if angle-of-attack and sideslip information are included, they be presented on the director needles of the attitude indicator. The recovery of the aircraft from unstable flight regimes in case of damper failure may be manually possible if these needles are properly "quickened". A study of manual flight in all flight regimes by means of such a scheme is recommended as a further human engineering effort.

Visual Landing Aid

Aircraft accidents can be naturally reduced by improving the instrumentation used for landing. This improvement can be realized by considering both the human engineering and aerodynamic problems involved. Minneapolis-Honeywell is currently working in areas which are directly applicable to this problem and is contracted to WADC to develop and produce a practical landing system.

Over one-half of all Century series aircraft accidents are in landing; most of these accidents are due to pilot judgment error. Honeywell has completed the initial phase of developing a visual landing aid and will be conducting flight tests in conjunction with WADC to prove flight-test feasibility. The initial studies have indicated that a pilot aid is possible which may save a considerable number of aircraft. A computer study of all factors associated with the problem was used to develop the hardware configuration to be flight tested. This has resulted in a development of a system as shown in Figure 38. Figure 39 illustrates the general concept of the instrument.

While flying along a straight-line descent path toward a ground target, the angle at the pilot's eye between the horizon and the target remains essentially constant and is the descent angle. Variation of the angle between the horizon and the target indicates that the aircraft is not following a straight-line descent path. Lane and Cumming attribute some under and overshoot landing accidents to distortion of this visual cue due to use of false horizon (because of weather, external illumination and/or mountainous terrain) and pilot inability to use this cue properly (reference 35). Provision of a horizon-stabilized vertical protractor would aid the pilot in determining when to start descending and in monitoring the angle between the horizontal and the target point in order to maintain a desired descent path.

The vertical protractor can only give position information at a given instant, and, at the small angles involved for the usual descent paths, rate information is difficult to extract and use from this display alone. As a further aid it is considered desirable to include instantaneous flight path to provide information on where the aircraft is actually going with respect to the earth at any instant. This display element informs the pilot of an impending deviation from the desired descent path because of changed flight direction and allows flight control adjustment to be initiated in the proper direction appreciably sooner than if the vertical protractor alone were used.

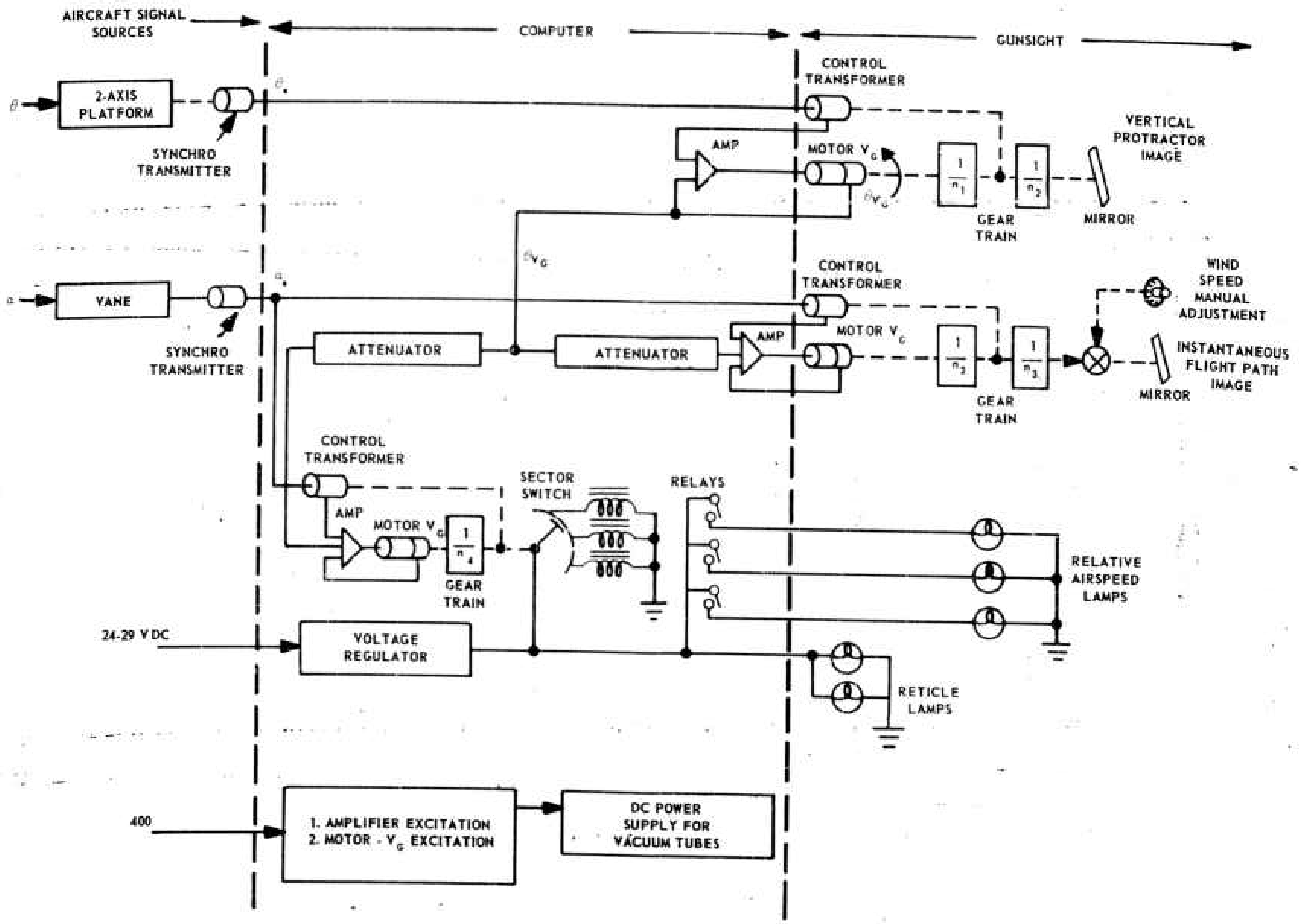



Figure 38. Landing Aid System Diagram

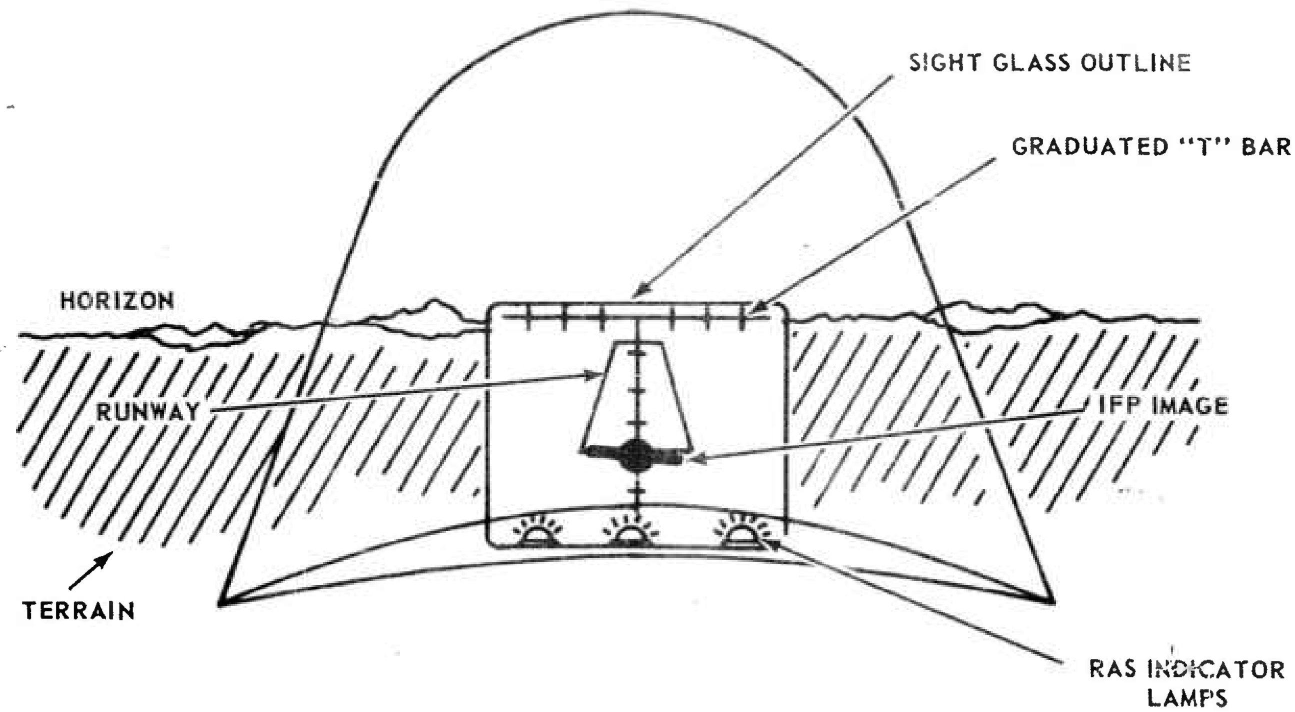



Figure 39. Landing Aid System Display

During the landing descent it is desirable to establish as slow an airspeed as possible while maintaining a safe margin above stall speed. Provision of relative airspeed with respect to desired airspeed as a display element of the sight system will allow the pilot to monitor airspeed while keeping his vision out of the cockpit during the descent. A three-lamp sequence has been provided in the Phase I simulation with favorable results. By this display method the pilot is allowed to concentrate on the direction images and obtain speed information without refocusing his eyes on a needle at finite distance or attempting to decipher a cluttered display.

Communications Control Panels

A physical relocation of communications controls is suggested as shown in Figure 40. The link studies (in Part I, Analysis) indicated that the communications equipment would be suitable for integration. If no unsuitable coupling effects are developed by the relocation, it would be desirable from the operators point of view, both in enabling him to quickly locate a given piece of communication equipment and in facilitating the use of the equipment by its preferred location.

The communications panel occupies 84 square inches on the right console. The separate areas which were occupied by the various radios in the Phase I cockpit covered an area of 132 square inches. Thus 48 square inches of console space is saved by the new configuration.

The individual radios were arranged in columns and, where possible, similar functions are seen across the rows. Sufficient information on the use and operation of the communications equipment was not available to enable a quantitative estimate of the reduction in pilot workload to be made. However, it is believed that the difference will be significant.

Remainder of Instruments

All other instruments will remain essentially as in the Phase I recommendation. The displays are relocated according to the results of the analysis in Figure 33.

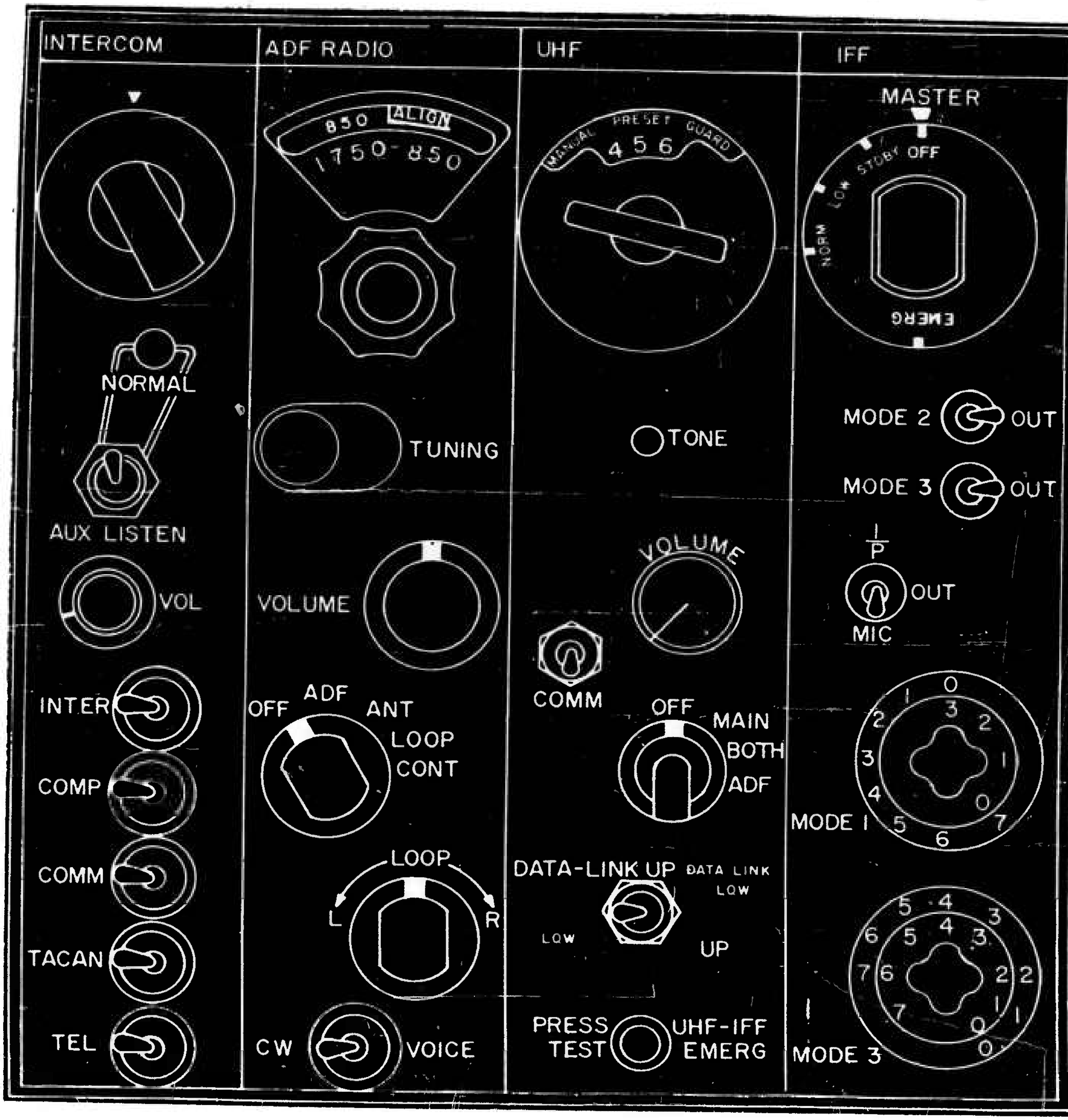



Figure 40. Communications Control Panels

## II RECOMMENDATIONS

# SECTION II

## REAR COCKPIT FLIGHT CONTROL INSTRUMENTATION

## RECOMMENDATIONS

Certain recommendations can be made concerning the navigator's position as the result of the analysis and study. These are of necessity incomplete since the study was confined to the pilot's cockpit and general flight control instrumentation. The exact navigator-observer workload is not known but is presumed high in certain aspects of the flight. On this basis the following items are proposed:

1. Fuel Management Display

The results of the Honeywell fuel management study casts serious doubt that the crew can handle the fuel problem with the facilities available in the Phase I cockpit. This leaves the problem to the ground control facilities or requires a reduction in the combat radius of action. The recommendation was made that a data acquisition, computation and display system be developed for the aircraft.

This system displays the following information to the navigator in analog form:

Maximum range at optimum conditions

Range to base

Tactical fuel reserve

Landing reserve

Total fuel quantity

2. Vertical Situation Indicator for the Navigator Station

A brief analysis of the mission requirements of altitude information needed by the navigator was made. It lead to the recommendation of a linear planning scale display which presented target, command and altitude information in an analog relationship. This indicator is described in CR-ED 1016 (34).

## SECTION III

## SUGGESTED FUTURE PROGRAM

In conclusion, it is felt that the communication of information cannot be completely accomplished by written means. The authors welcome questions and the opportunity to discuss the analysis and recommendation found in these few pages.

The following list is suggested for the next step in the program:

1. Build equipment to evaluate recommended Phase II cockpit system (Figure 33).

2. Evaluate recommended system with simulation techniques and flight test.

3. Study manual control of the aircraft in the nondamper or basic airframe mode. Develop "quickened" display to allow emergency recovery of aircraft from dangerous flight regimes.

4. Analyze the navigator workload and the possibility of a one-man operation. The use of information theory and a study of the navigator equipment will allow an accurate estimate of the feasibility of such a move.

5. Continue the development of the revolutionary cockpit to the point where a specific recommendation can be made and evaluated.

6. Analyze pilot workloads in contemplated missions which differ from the basic one and determine the necessity and value of new instrument systems.

# APPENDIX

## "REVOLUTIONARY" COCKPIT

The recommendations of this report (Sections I and II) were base on a typical high-performance intercept mission. This mission is described in terms of today's weapons and tactics. In order to be immediately meaningful, efforts were made to be hardware minded and practical in the study and recommendation. A second aspect of the aircraft concerns the future extension of the weapon system from a human engineering standpoint.

The question to be answered is: "What system will allow the crew to make a maximum contribution to the future use of the weapon?" It is admitted that the boundaries of the present "state of the art", economic and political background and complete analytical justification are usually violated by such futuristic thinking. For this reason, the ideas or suggestions offered in this section are presented in broad outline which can, in most cases, be further explained and defended.

The future tactical use of the manned interceptor, although a question mark, has potential when man's capabilities in judgment and analysis of the complex situation are used. The "revolutionary" cockpit presented in this section is aimed at using these capabilities.

The operator is given a cockpit tailored to give him tactical planning capability, means of implementing his decisions and control of his vehicle. The combat problem is not reduced by the cockpit to a push-button level, but requires skillful activity by a well-trained, intelligent pilot. The flexibility and capability of man then complements the equipment and provides a means of extending its use.

The "revolutionary" cockpit is therefore an attempt to consider further advancement of the aircraft by stepping beyond the present limits of the "state of the art". Thought of further significant contribution to the aircraft's development raised the question: "Could the full use of automatic flight control and data input equipment allow the aircraft to be flown as a one-man interceptor and still retain its weapon sophistication?"

In order to properly answer this question an extensive study of the rear cockpit task would have to be undertaken. Such a study was beyond the scope of the present effort. However, in the process of the mission analysis, in examining the pilot's task at the points at which he interacted with the man and equipment in the rear cockpit, ideas for integration of the tasks and the associated instruments were generated.

Present equipment and ground facilities are such as to make a two-man interceptor highly desirable. Interviews with pilots who have flown both F"X" and F-"Y" aircraft point to the present value of the two-place aircraft. Improved equipment and increased automation may make the one-man interceptor desirable from such aspects as weight saving and internal coordination. In extending the aircraft into the future, it is important to consider the potential of a

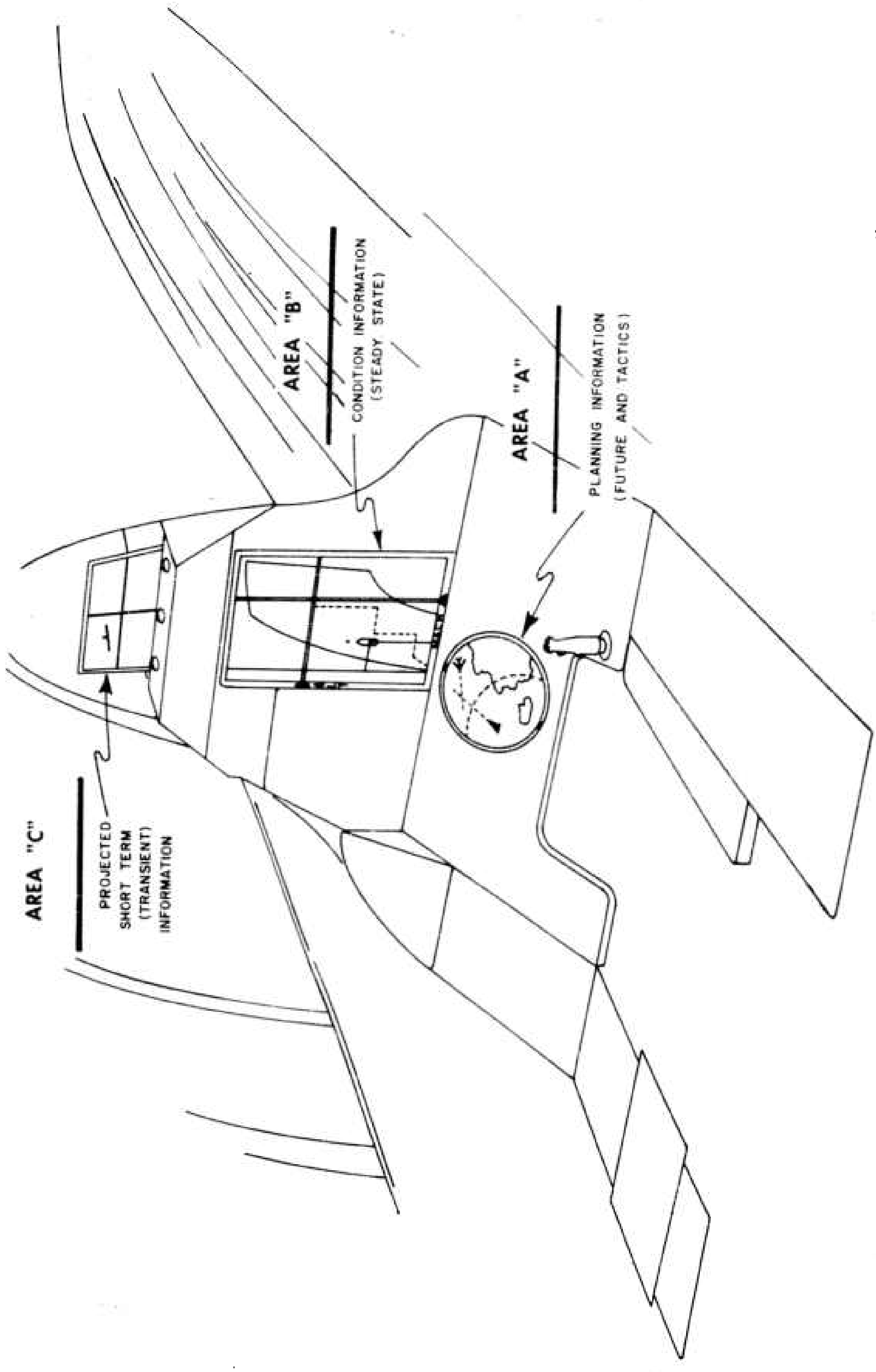



Figure 41. "Revolutionary" Cockpit Framework

one-man operation. The analysis of the case where the autopilot was used to its full capability indicated that the pilot might be able to handle the entire job. Although the lack of exact knowledge of the rear cockpit workload clouds the issue, a single-place cockpit was designed.

Figure 41 presents the framework for the cockpit. The time limitation of modern air combat is recognized and an orderly breakdown is provided in three areas. A planning area "A" is centered about a horizontal situation display. Here the pilot can plan his overall tactic so as to insure success. Such considerations as time relationships, weapon launch limitations, available fuel energy, alternate targets and return-to-base problems can be manipulated to decide upon the best tactics. Normally, the autopilot must tend the transient problems and maintain the aircraft in a prescribed flight during this stage. Once a decision of total plan is reached the pilot then would proceed to area "B" to insert information into equipment to establish the conditions he desires the aircraft to attain. As an example, he may decide a maximum climb to altitude followed by a maximum fuel economy cruise to a geographical area on a particular heading is required.

Area "B" is centered around a display of his primary flight envelope and his present condition within it. The automatic equipment will then program his flight which can be checked at each point of time by the condition information in area "B".

Area "C" provides a means of manual control of the aircraft in terms of the pilot's control requirements. It contains such information as is necessary in landing by AGCA or flying the final attack. It is anticipated that the combat mission would seldom rely on the use of area "C" but that it would be used in ordinary flight problems of landing and takeoff.

The "revolutionary" cockpit is shown in Figure 42 in more detail. The equipment previously located in the rear cockpit is integrated with the necessary functions of the front. In order to handle the workload and improve the information available to the pilot, certain major instrument changes are suggested. The principle planning or tactical instrument is the horizontal situation indicator. This is similar to several existing hardware designs, but furnished certain unique functions.

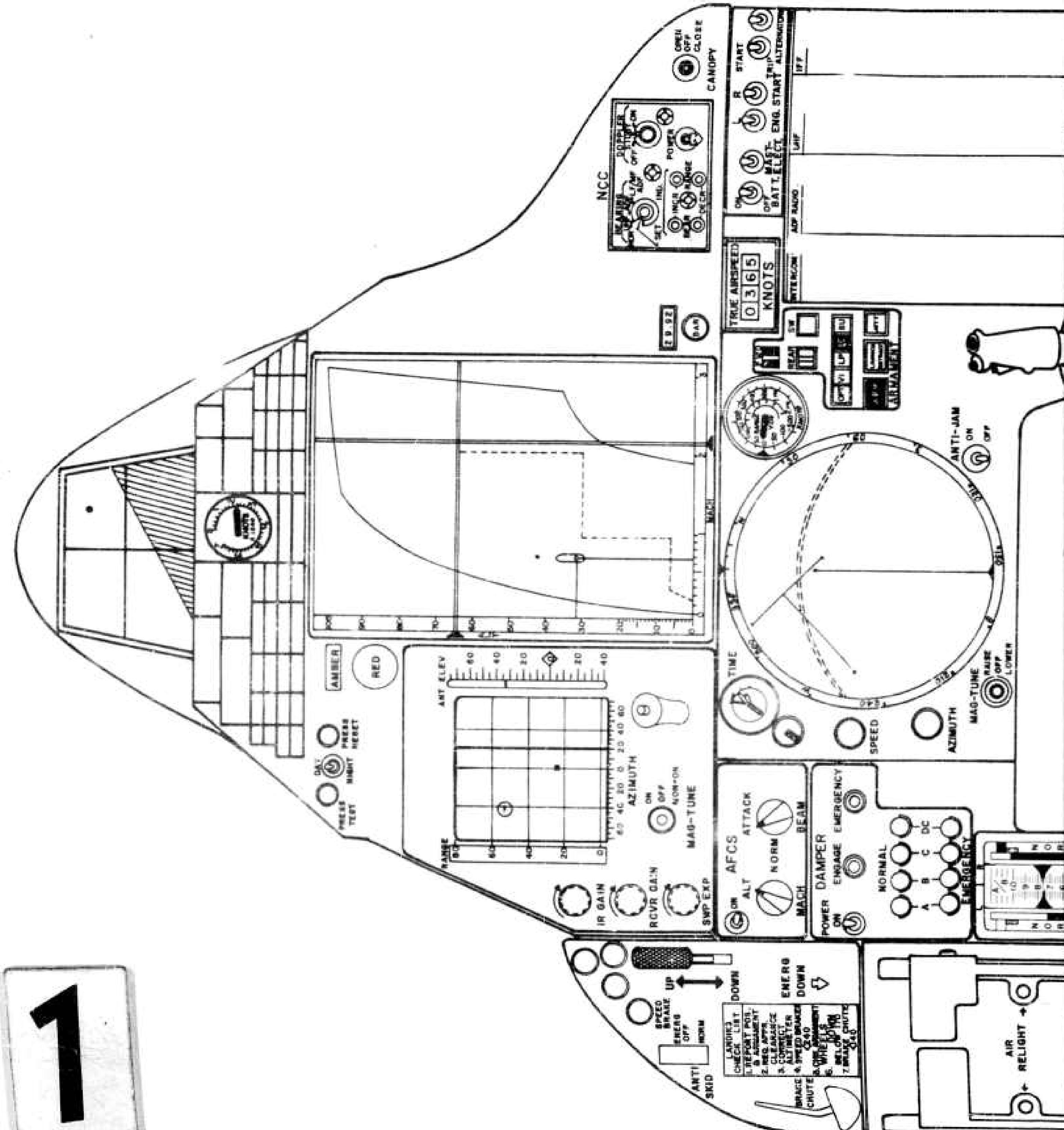
HORIZONTAL SITUATION INDICATOR AND PLOTTER

The horizontal situation indicator and tactical plotter is an analog presentation of the overall mission in planview. It allows the operator to try out certain tactics and evaluate the probable results of such tactics. One a tactic has been acted upon it allows the pilot to monitor the progress of the attack.

The following are the desirable features of this plotting board, assisting the pilot in the following ways:

1. He can see, at all times during the mission, the bogey's position and his own position, relative to each other and any available ground references.

2. He can also see a predicted position of the bogey after n minutes and simultaneously his own possible positions in space after n minutes (n = any time value the pilot selects).


CANOPY
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DOPPLER
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ENG. START
BATT. ELECT.
IFF
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INTERCOM
TRUE AIRSPEED
0365
KNOTS
ARMAMENT
ANTI-JAM
ON
OFF
MACH
TIME
SPEED
AZIMUTH
MAG-TUNE
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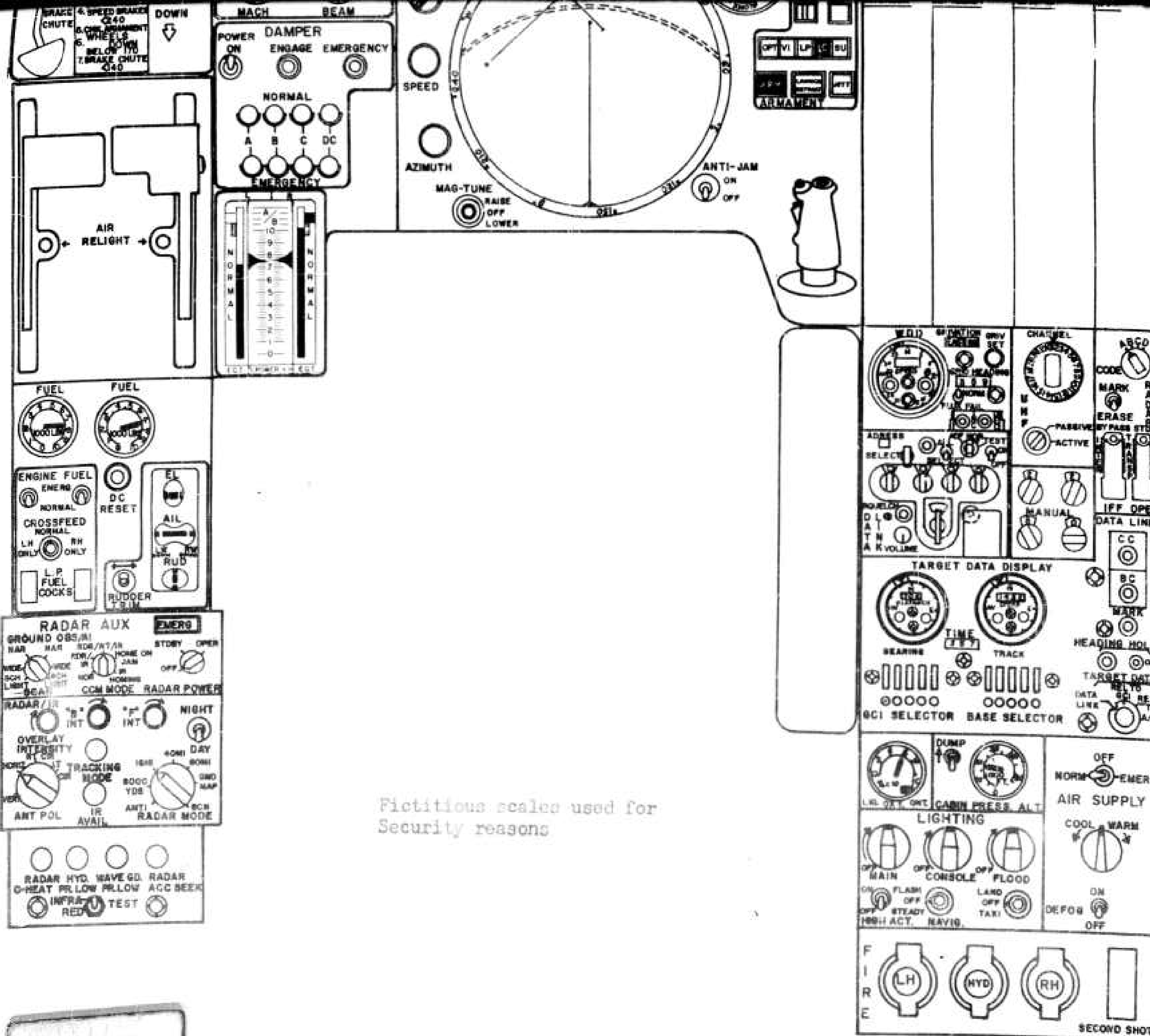


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Figure 42. "Revolutionary" Cockpit

3. He can select any of a great number of possible intercept courses; his selection based on: (a) the quickest possible intercept, (b) the course which optimizes his range (at a low speed to reduce fuel consumption), or (c) the mode of intercept desired: lead-pursuit, lead-collison, snap-up.

4. He can plot this course as soon as he receives radar information on the bogey and he should be able to set up the entire course in less than five seconds. Further, he can replot the course in the same amount of time in the event of any evasive maneuvers of the bogey.

5. This plotting board can show him a decreasing circle of available range, for navigating to base after the interception.

6. It can also locate the base on the projected map, so that he can see at a glance if it is within flying range, and, if so, he can plot his heading and flying time to the base.

7. He can use the board for plotting and, when the course is set up, can feed command signals directly to the AFCS (or instrument directors for manual flight).

The following use of the display-plotter is given as an example of the use the pilot will make of the system.

As soon as the controller receives ground radar signals which locate the bogey on his plotting board (which may be before the interceptor has left the ground) he will be able to set up the intercept course. He will select a speed setting and begin increasing his time control (swinging the interceptor's arrow toward the offset point which is seen as attached to the bogey's vector).

At this point it may be apparent that his arrow will not reach the offset point. He has a choice of increasing the time control or increasing the speed control. If he chooses to increase the time it will extend both arrows (but the interceptor's more than the bogey's because the interceptor is now at a higher speed than the bogey) and, by readjusting the flight path control he will be able to match the end of arrow with the offset point. If instead, he chooses to increase his speed control, he can thereby lengthen the interceptor's arrow without changing the bogey's arrow, and in this way locate it in the offset point.

Up to this time both the terrain features and bogey symbol and its position-predictor arrow) have been moving on the plotting board toward the fixed interceptor symbol. The arrows have stayed at the length selected by the operator and the time readings on the "minutes" display has remained at the last setting the operator chose.

At this point (having located the interceptor's arrow in the offset point), the operator pushes the AUTO button. This feeds the command speed and heading to the autopilot (or pilot's directors) and the time clock is activated (the hand moves toward zero as time passes). Now the ends of the arrows are fixed with respect to the space coordinates and the arrow lengths decrease as the "bugs" fly up to the chosen "collision" point.

If the interceptor's arrow becomes slightly dislocated from the desired position (the offset point), because of the time lag from command signals to response, the operator can make fine corrections, varying any of the three controls to correctly reposition the arrow.

Because the ends of the arrows will be moving until the AUTO button is pushed, it will be difficult to set the exact intercept course. It would be likely, therefore, that the operator would set up only an approximate heading and speed, and not make final corrections until after the AUTO button has been depressed.

Any evasive maneuvers of the bogey could be instantly detected by the operator as the bogey's offset point shifted away from the interceptor's arrow. By changing any (or all) of his three variables (speed, time, heading) he could quickly replot a new intercept course.

When the interceptor reaches the offset point, he will be 50 miles from the point of "collision." The pilot would then use the radar scope for the final attack. The navigator would, of course, benefit from the use of this instrument in a two-man plane.

Estimates of the size and complexity of the system have been made. In order to include the instrument, it may be necessary to use a "side" stick.

The control consoles of both cockpits have been integrated into the cockpit and sufficient room seems to be available if certain changes such as indicated in the drawing can be made.

FLIGHT ENVELOPE AND COMMAND INDICATOR

This instrument presents a picture of the condition of the aircraft with respect to its flight envelope, and the command information of speed and altitude. An aircraft's limiting flight characteristics are often best described in terms of its "flight envelope". This is a graphical representation of the limits due to such factors as structure, engine and stall. High performance aircraft capable of a great range of airspeeds encounter new variable limits.

Some flight regimes are dangerous if automatic stabilization equipment is not available. The complex relationship of the aircraft to its flight envelope leads to a number of difficulties. The first effect is a waste of aircraft capability due to the pilot's flying too convervatively within the limits. Thus aircraft performance which has been obtained at great cost is never used. Another effect will be a confused display situation resulting in a multitude of limit "bugs" or pointers, instrument knobs and safety markings on dials. A display is suggested which offers a solution to this problem, the flight envelope indicator.

As seen in Figure 42, an instrument is shown which contains a typical flight envelope. This graphical plot of the envelope describes continually the flight

limits of the aircraft in its present condition. Changes in external stores, temperature and allowable structural loading will be reflected in the shape of this envelope. Malfunctions in equipment causing changes in flight limits will also cause the envelope to change. The dynamic outline of the flight envelope then serves as an indication of equipment status as well as a memory of the flight limits.

Within this envelope an indication is found of the present Mach and altitude of the aircraft. The indication of aircraft condition is therefore directly related to its capabilities and decisions regarding changes in the conditions are made more safely and easily; flying into "coffin" corners will be avoided. The circle shown in the figure represents "g" limitations for the aircraft. It is to be noted that since the "g" limits are two dimensional, one can transmit fore and aft acceleration limitations which may be necessary with the advent of higher powered engines.

Command information can be included in a manner shown in Figure 42 along with information as to the proper sequence to use to attain the command in the most efficient manner. A maximum climb path is therefore a possibility where the operator can climb and accelerate his craft so that he uses all the capability of his equipment while staying within its limits.

Further information regarding possible speeds and altitudes which can be achieved within one or two minutes can be given on the instrument in terms of time contours. Hypothetically, an aircraft at M 0.8, sea level, could attain: M 1.5, 20.000 feet, in one minute; M 2.0, 40,000 feet in two minutes.

The flight envelope instrument could also be used to advantage in a two-place interceptor.

Standby information of aircraft condition will be chosen as needs are determined by reliability and other practical considerations.

The status panel is found in the area above the flight envelope instrument.

The search radar is included adjacent to the flight envelope instrument.

An optical projection instrument is found at the top of the panel to present flight and speed control information. Steering information for attack, interceptor guidance from AGCI, AGCA and other modes is found in this area.

The concepts described in this appendix show promise of a major system improvement. The value of the revolutionary cockpit to the anticipated future of the aircraft should be determined. For this reason the suggested future program found in Section III, page 178, recommends a continuation of the study.

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